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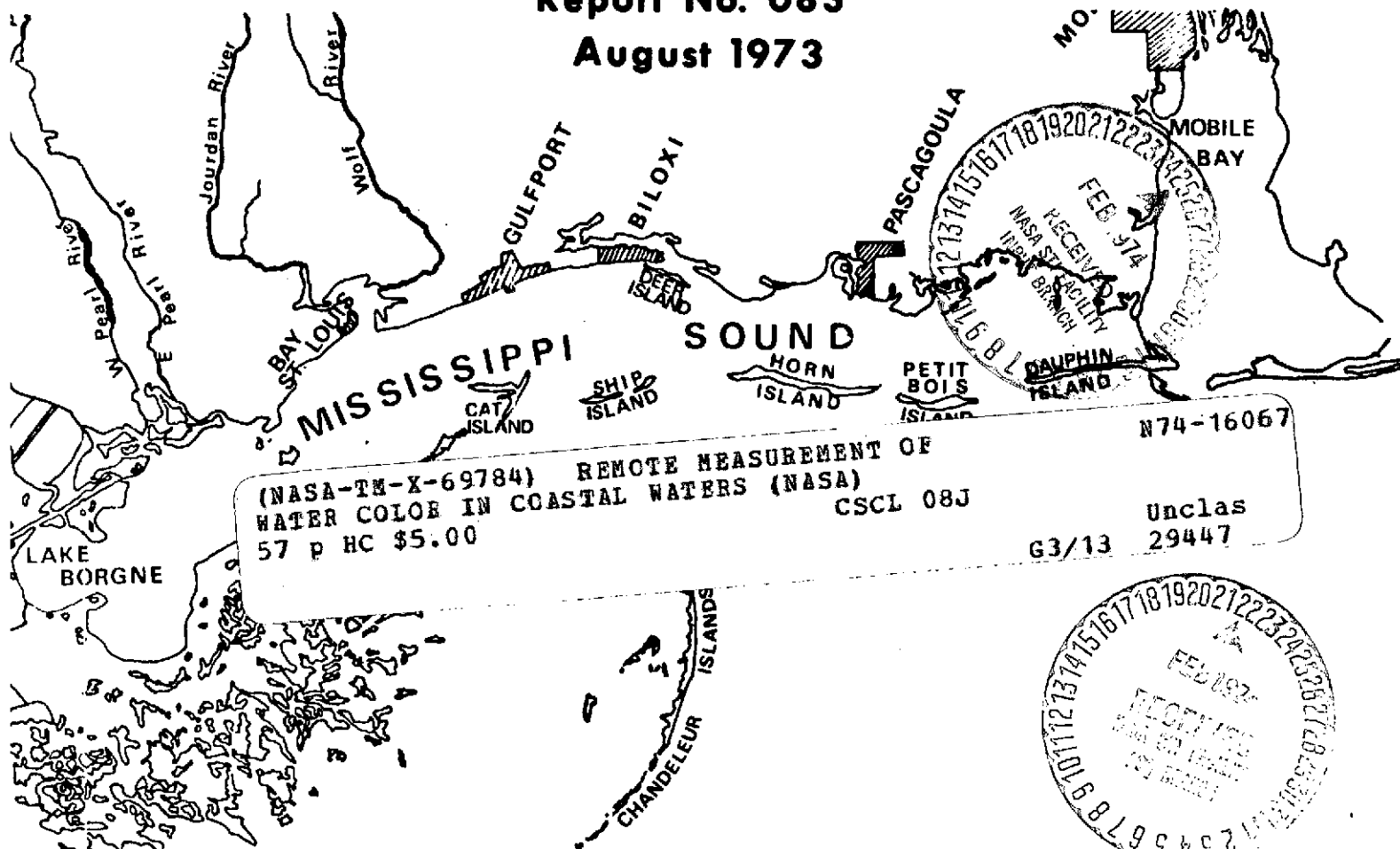
REMOTE MEASUREMENT OF WATER
COLOR IN COASTAL WATERS

By

J.W. Weldon

Report No. 083

August 1973



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Earth Resources Laboratory
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I

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INTRODUCTION

A study has been initiated with the objective of developing a quantitative method of determining chlorophyll and turbidity values utilizing spectral radiometer data collected over coastal waters with high chlorophyll and turbidity content. [7]

A number of investigators [1], [2], [3] have been studying the changes in the upwelling light from the sea caused by changes in chlorophyll concentrations. Investigators at Woods Hole Oceanographic Institute utilizing a TRW spectrometer in their research aircraft collected spectral data which demonstrates the feasibility of using ocean color as a parameter to detect chlorophyll over the range of concentrations characteristic of the open ocean. [1] The results are shown in Figure 1. The data show that as the chlorophyll concentration increases, the backscattered light decreases in the blue region and increases in the green region. The technique used for determination of sea truth chlorophyll was that proposed by SCOR-UNESCO working group 17 in Determination of Photosynthetic Pigments in Sea Water, UNESCO, Paris, 1969.

The backscattered radiance which emerges from the water surface is dependent on the concentration of particles and solutes in the water and the absorption properties of water itself. [2] The presence of these particles and solutes cause discoloring and obscuring in the water which is known as turbidity. One method of determining in-situ turbidity of water is to measure the extinction depth of a secchi disk. This is the method that was used to obtain the sea-truth values for turbidity.

The backscattered radiance received by the spectral radiometer is thus affected by both chlorophyll and turbidity. The determination of how these two parameters affect the spectrum will have to be established before quantitative values for these parameters can be obtained by remote sensing techniques.

The purpose of this report is to present some of the preliminary results that have been obtained in the relationships of the spectral radiometer data to selected Mississippi Sound water parameters.

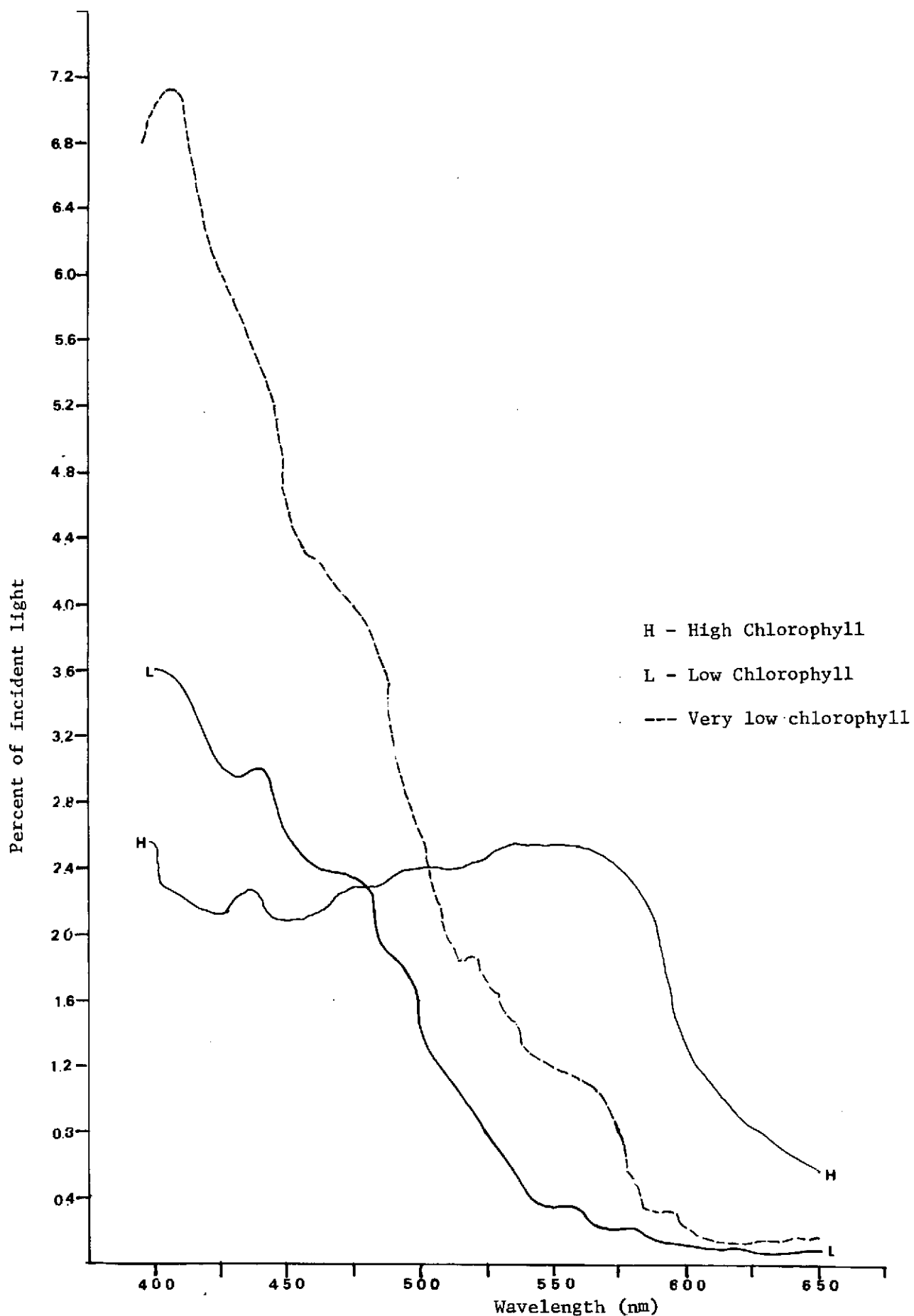


Figure 1. Data from the high and low chlorophyll curves plotted as percentage of the incident light and compared with data taken on the same day from an area with very low chlorophyll concentration south of the Gulf Stream (after Clarke 1970).

OBJECTIVES

The initial phase of the study utilized existing spectral radiometer computer programming capability to investigate the feasibility of correlating selected wavelength radiance values with chlorophyll and secchi visibility data obtained from sea truth samples.

The information gained about the characteristics of the spectral data from the Mississippi Sound waters during this phase would then be used subsequently to develop a statistical technique for determining chlorophyll and turbidity values from the spectral radiometer data.

The first objective of this initial phase was the extrapolation of the method of determining chlorophyll concentrations in the open ocean to remotely sensed chlorophyll in the turbid waters of the Mississippi Sound.

The second objective of this study was to determine wavelengths in the backscattered spectrum which could be used to remotely measure turbidity, turbidity being characterized by the secchi depth of the water.

Additional objectives of this initial phase in the water color study are to establish some basic characteristics of the spectral radiometer data obtained from the water in the Mississippi Sound. Among these were: (1) repeatability of the water spectrum signatures from flights over the same area; (2) the effect that changes in altitude have on the water spectrum signatures; (3) the wavelengths that are best for determining changes in chlorophyll concentrations and secchi visibility; (4) the effect changes in sun angle have on determining remotely sensed values for chlorophyll and secchi visibility.

REMOTELY SENSED DATA

Spectrometer Capabilities

The instrument that was used to collect the spectral data was an Exotech Model 20-D spectral radiometer. This instrument is based upon a circular variable filter approach. The instrument uses a Si detector and is capable of measuring the .36 to 1.24 micron spectral region. The field of view is 0.75° and one complete spectrum is obtained per second. The instrument was mounted in a Beech E-18 aircraft and was pointed at nadir. The spectral data was recorded on an Ampex AR700 magnetic tape recorder.

Flight Line Selection

The spectral radiometer as well as other remote sensors has been flown on a number of water parameter surveys in the Mississippi Sound area. The flight lines used in the initial water color investigations were selected from these surveys.

The flight lines were reviewed to see how well they conform to the following criteria:

- o Large variation in sea truth (chlorophyll and secchi visibility).
- o Multiple flights flown over the same area at different altitudes.
- o Good meteorological conditions (little haze and cloud cover).
- o Spectral radiometer and aircraft data system operating correctly.

Flight lines flown on July 24, 1972, August 4, 1972 and August 7, 1972, in the Mississippi Sound and October 18, 1972 in Biloxi Bay best meet the above requirements.

July 24, 1972 - Mississippi Sound

This mission contained four flights over the same area, two at 10K feet and two at 2.5K feet.

The flight was approximately 2 hours later than originally scheduled. A failure in the RS-18 scanning radiometer caused the delay. This delay caused the Beech overflight not to coincide very well with the sea truth. (Figure 2) The sky was clear, but hazy, and the spectral radiometer operated satisfactorily.

August 4, 1972 - Mississippi Sound

The Beech flight lines for this mission were the same as for the July 24 mission. Since only one sea truth boat was used, the time difference between aircraft overflight and sea truth measurements for all stations, except station "A", was extensive. (Figure 3) The sky was clear and the spectral radiometer operated satisfactorily.

August 7, 1972 - Mississippi Sound

All flight lines on this mission were flown at 10K feet. Two east/west flight lines down the Sound and one north/south across the Sound were processed. (Figures 4, 5 and 6) The meteorological conditions were good for the flight. There was extensive sea truth on this mission since it was a main ERTS-1 experiment mission. However, there is up to five hours difference between the sea truth measurement times and the time of the aircraft overflight. When two measurements were obtained at a sea truth station at different times, the measurement obtained closest to aircraft overflight was used as the sea truth value for that station. The spectral radiometer operated satisfactorily.

October 18, 1972 - Biloxi Bay

This mission contained three flight lines flown at 2K feet. The number of bridges and land areas in the field of view of the spectral radiometer and the small number of sea truth stations reduced the amount of spectral data that could be used from this mission. There was heavy haze during the mission, and the spectral radiometer was operating satisfactorily.

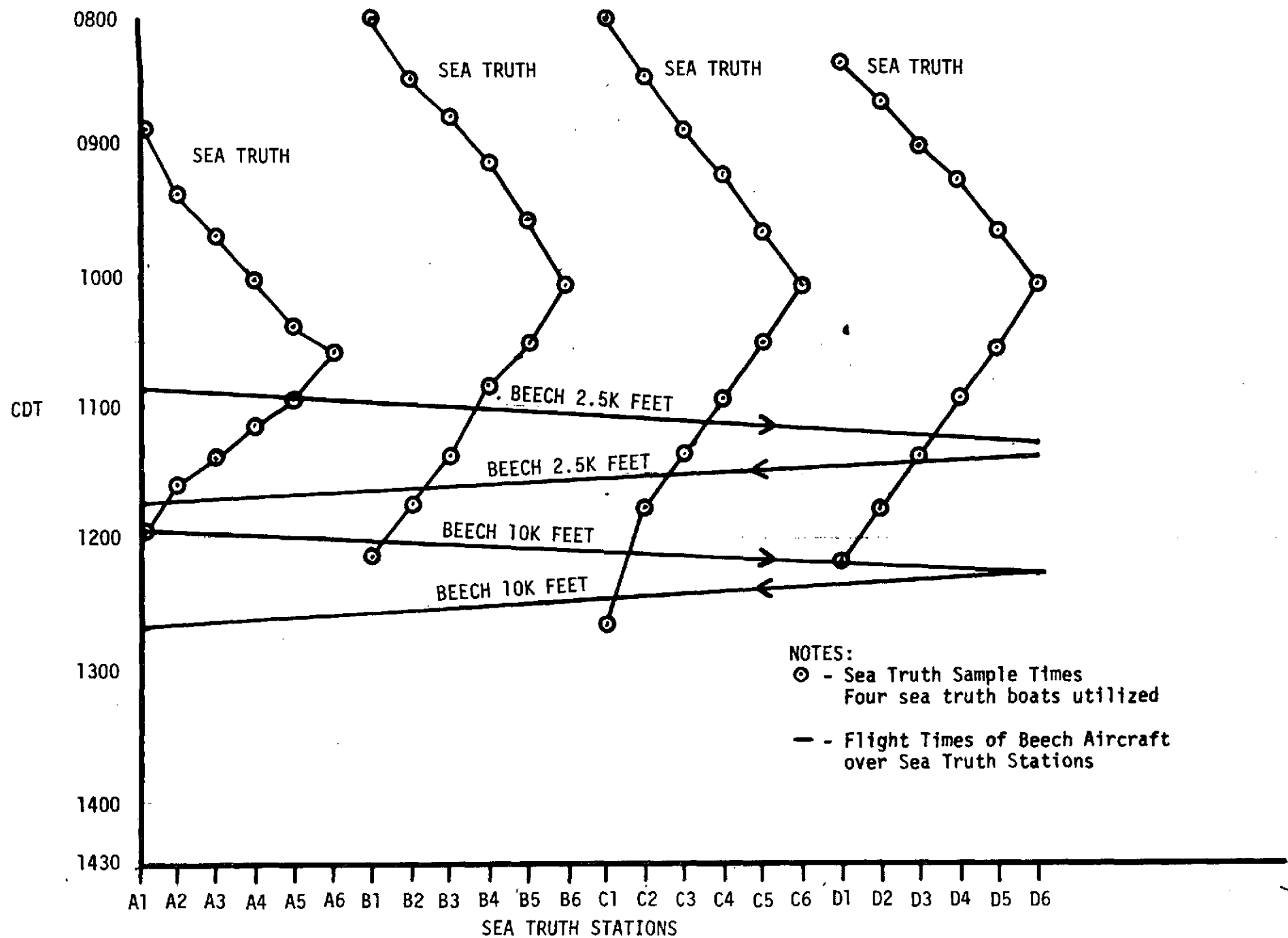


Figure 2. ERL Beech aircraft overflight conducted July 24, 1972, Mississippi Sound Mission

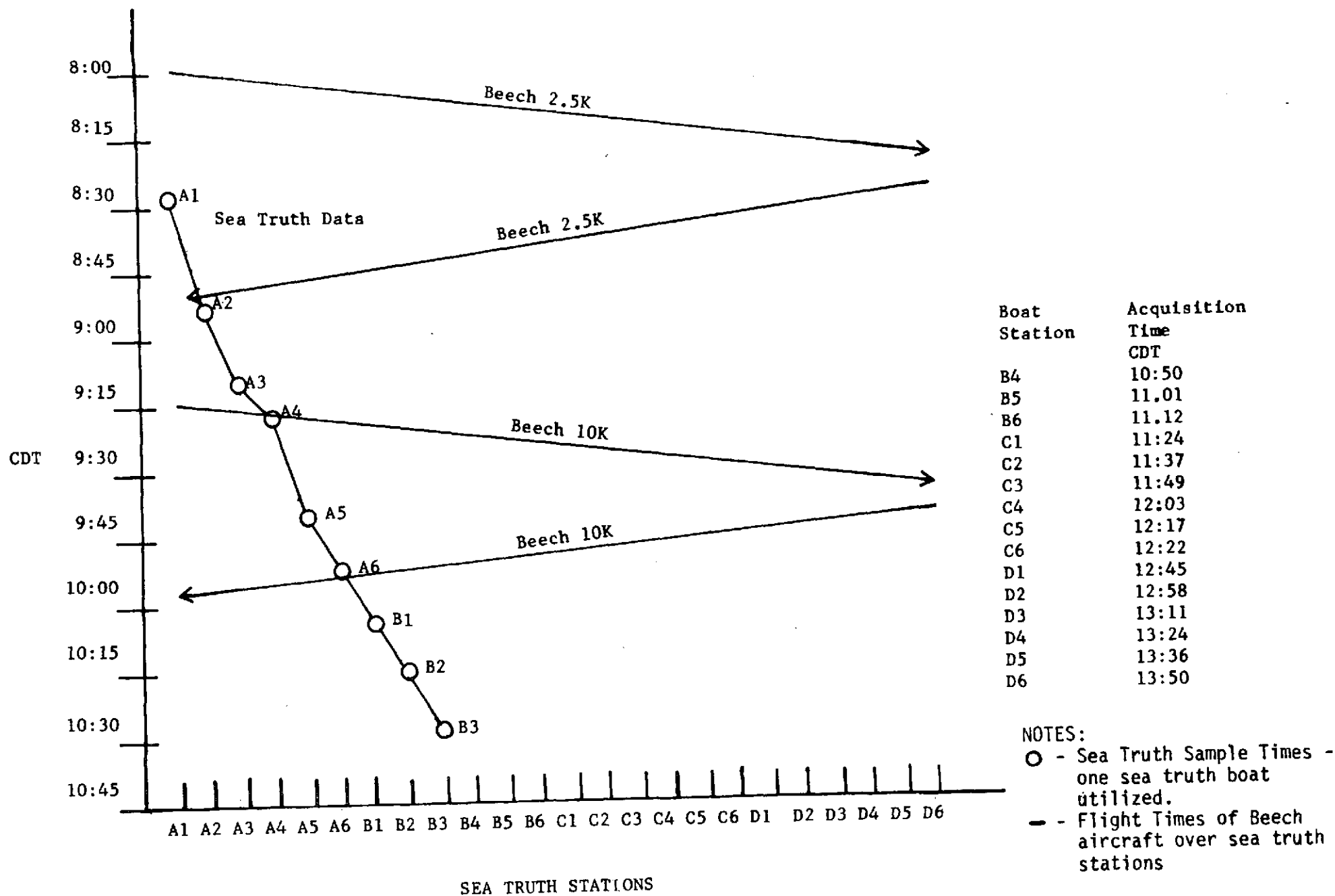


Figure 3. ERL Beech aircraft overflight conducted August 4, 1972, Mississippi Sound Mission

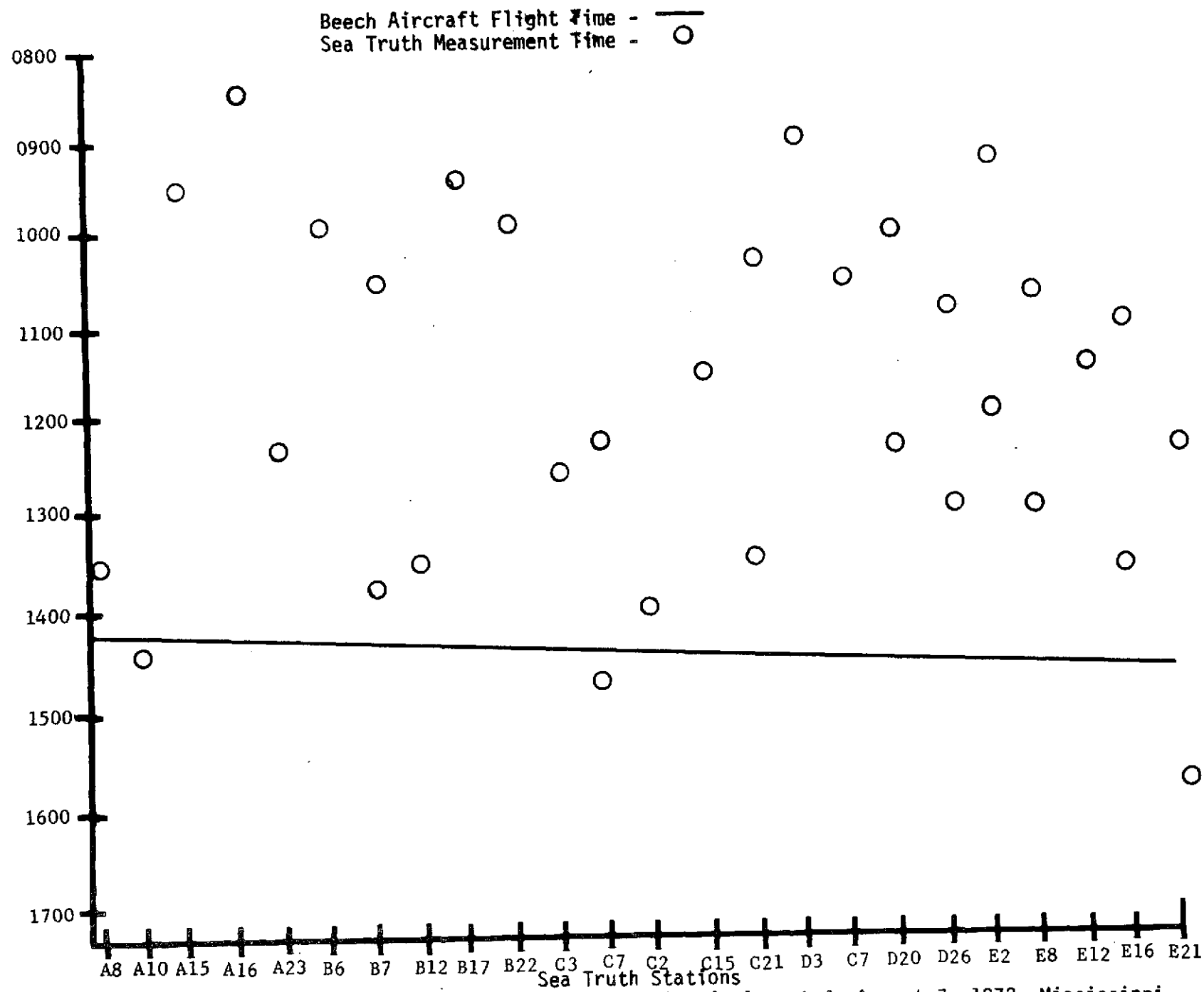


Figure 4. ERL Beech Aircraft overflight, Flight line 4, August 4, August 7, 1972, Mississippi Sound Mission

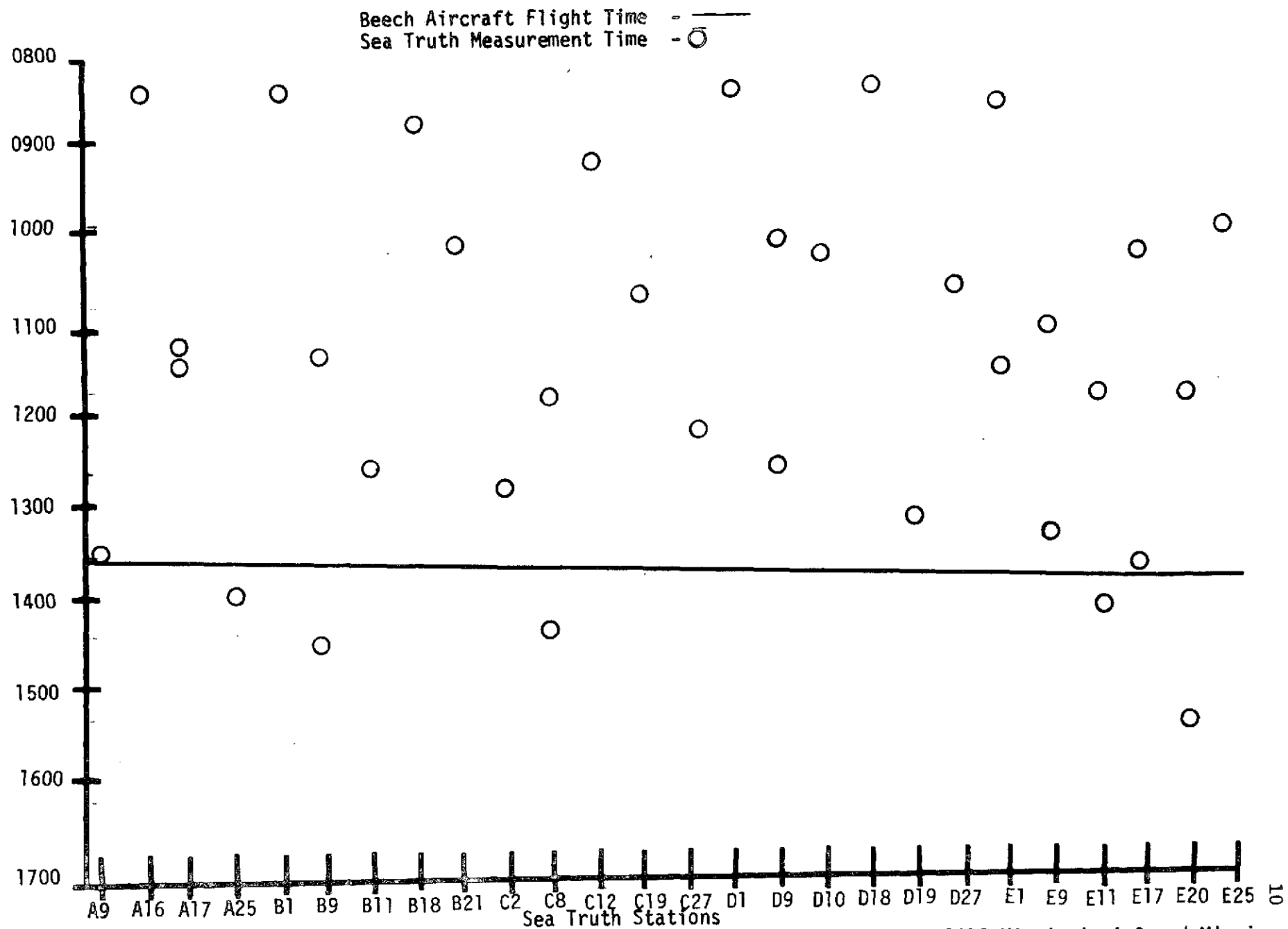


Figure 5. ERL Beech aircraft overflight, Flight line 5, August 5, August 7, 1972 Mississippi Sound Mission.

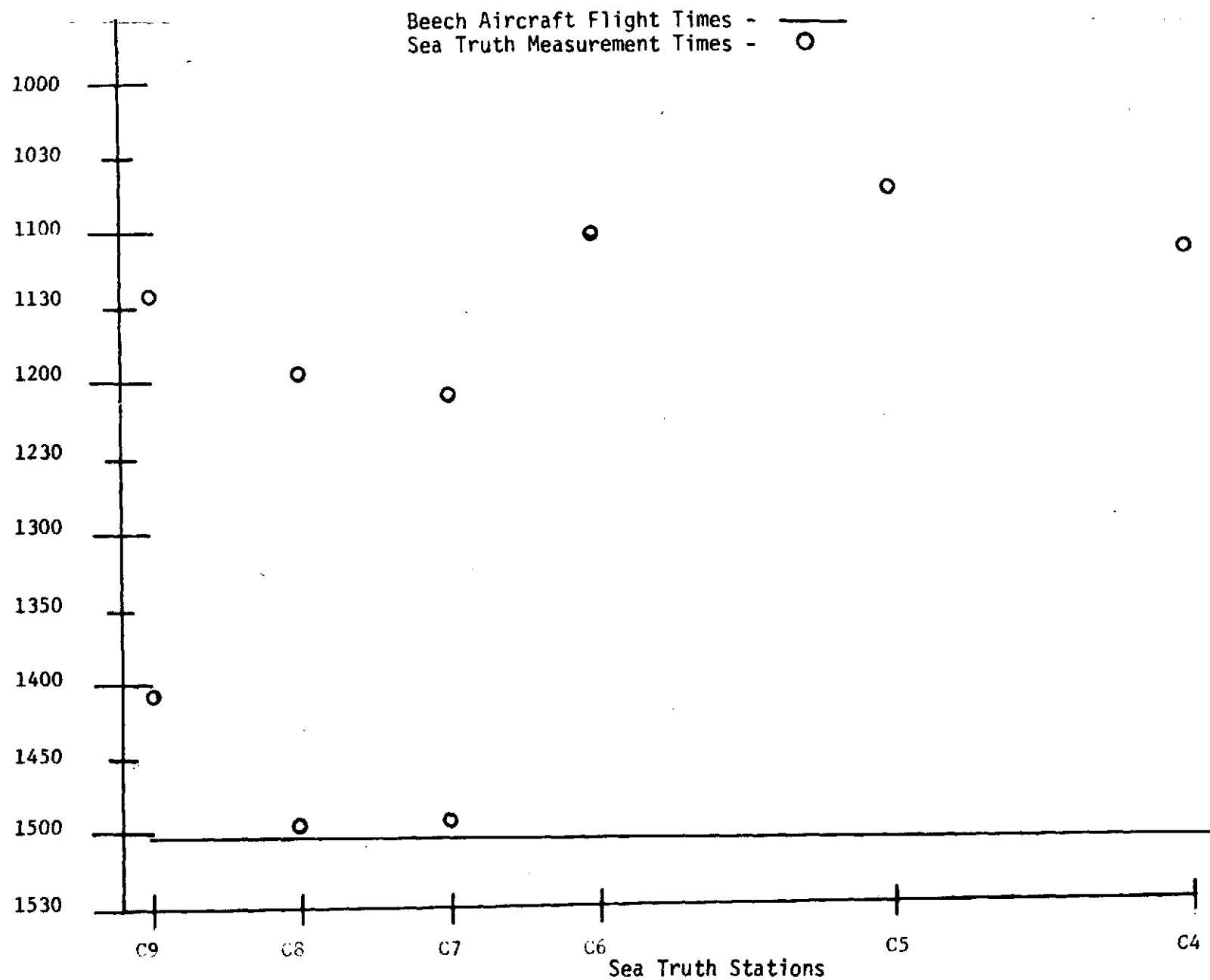


Figure 6. ERL Beech aircraft overflight, Flight line C2, August 7, 1972, Mississippi Sound Mission

SPECTRAL RADIOMETER DATA PROCESSING

Spectral Radiometer Calibration

The E-20-D spectral radiometer was calibrated in the ERL calibration laboratory utilizing standard techniques recommended by the manufacturer. The spectral radiometer was calibrated at the following wavelengths: .41 through .660 microns at 0.01 micron increments and .69 through 1.290 microns at .02 micron increments. The spectral radiometer is calibrated in radiance per unit wavelength intervals ($\text{watts/cm}^2/\text{SR/micron}$). The associated calibration computer programs assume that all the spectral flux incident on the spectral radiometer is emitted from the earth's surface. The effects of the atmosphere have to be removed before this is correct. The atmospheric effects were not removed during this investigation.

Computer Programs

The analog spectral radiometer data tapes from the aircraft are digitized at the Slidell Computer Center (MSFC) utilizing the SDS930 computer, the A/D system and a computer program prepared by Computing and Software Incorporated for this applications.

ERL has developed a spectral radiometer software program which retrieves the recorded data from the previous prepared digital tape to provide the following information:

- o Voltage versus filter wheel pulse position (tabulation)
- o Voltage versus wavelength (plots and tabulations)
- o Radiance versus wavelength (plots and tabulations)
- o Radiance of selected wavelengths versus time (plots)
- o Ratio of selected wavelengths versus time (plots)

The capabilities and execution procedures for this program are covered in "User Documentation Phase II, IR Spectral Radiometer Program." [3]

These programs were used to process the spectral radiometer data that was analyzed in this report.

Sea Truth

The sea truth data used to evaluate the spectral radiometer was collected using the standard ERL procedures for sea missions. A summary of the sea truth data and collection procedures are included in Appendix A for reference purposes. The detail collection and laboratory analyses procedures and additional sea truth data for these missions may be obtained from the ERL sea truth report for each mission listed in the Appendix.

Flight Line Repeatability

The two 2.8K foot flight lines flown on August 4, 1972 (Figure 7) were selected for determining the repeatability of the spectral radiometer. These flight lines more nearly overlap each other than other available flight lines. However, there was still only a few places along the line in which the foot print of the spectral radiometer from both lines viewed the same geographical area of water. These points were selected for comparison. The size of the spectral radiometer foot print at 2.8K feet and a ground speed of 140kt is approximately 33 feet wide by 236 feet long for one filter wheel revolution. It is assumed that the water is homogeneous in this foot print. The spectrum produced by the spectral radiometer is in reality derived from different segments of water in the foot print. The spectral wavelengths are evenly distributed along the length of this foot print. The radiance values for the blue wavelengths are thus obtained from one end of the foot print and the near infrared wavelengths radiance values from the other end of the foot print.

[See following illustration]

ILLUSTRATION 1

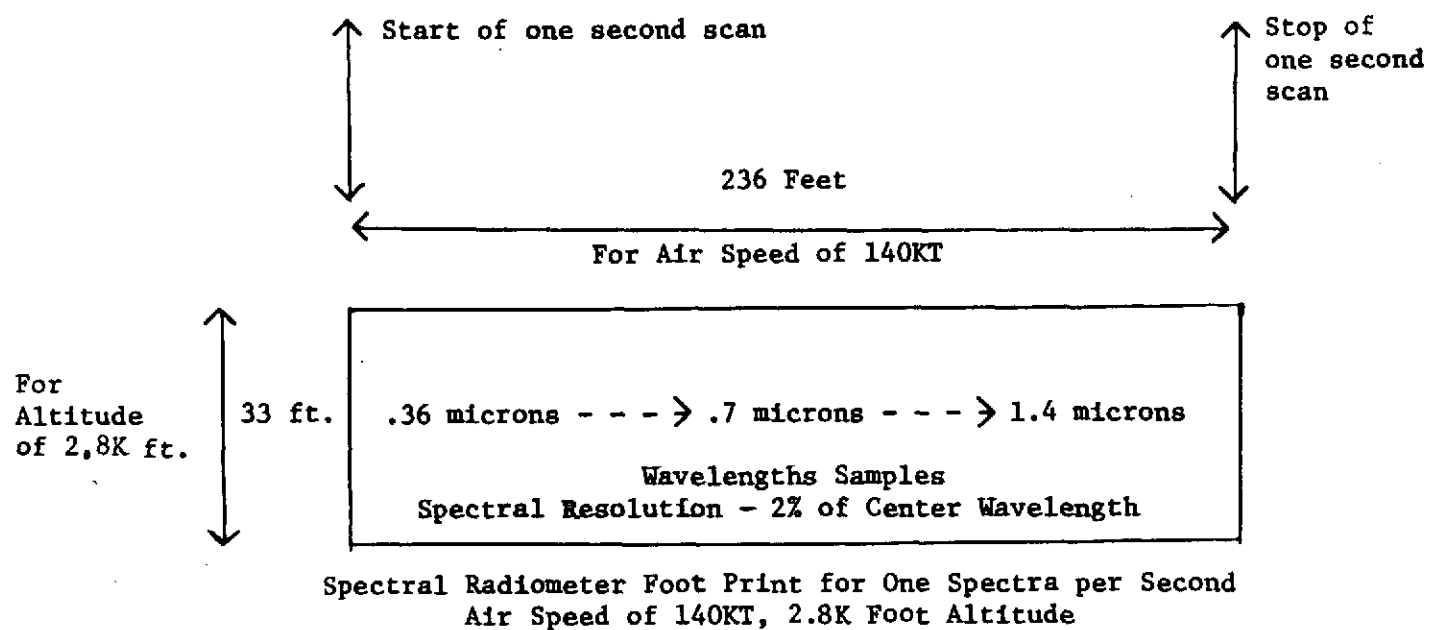


FIGURE 7. ERL BEECH AIRCRAFT FLIGHT LINES, 4 AUGUST 1972 MISSION MISSISSIPPI SOUND

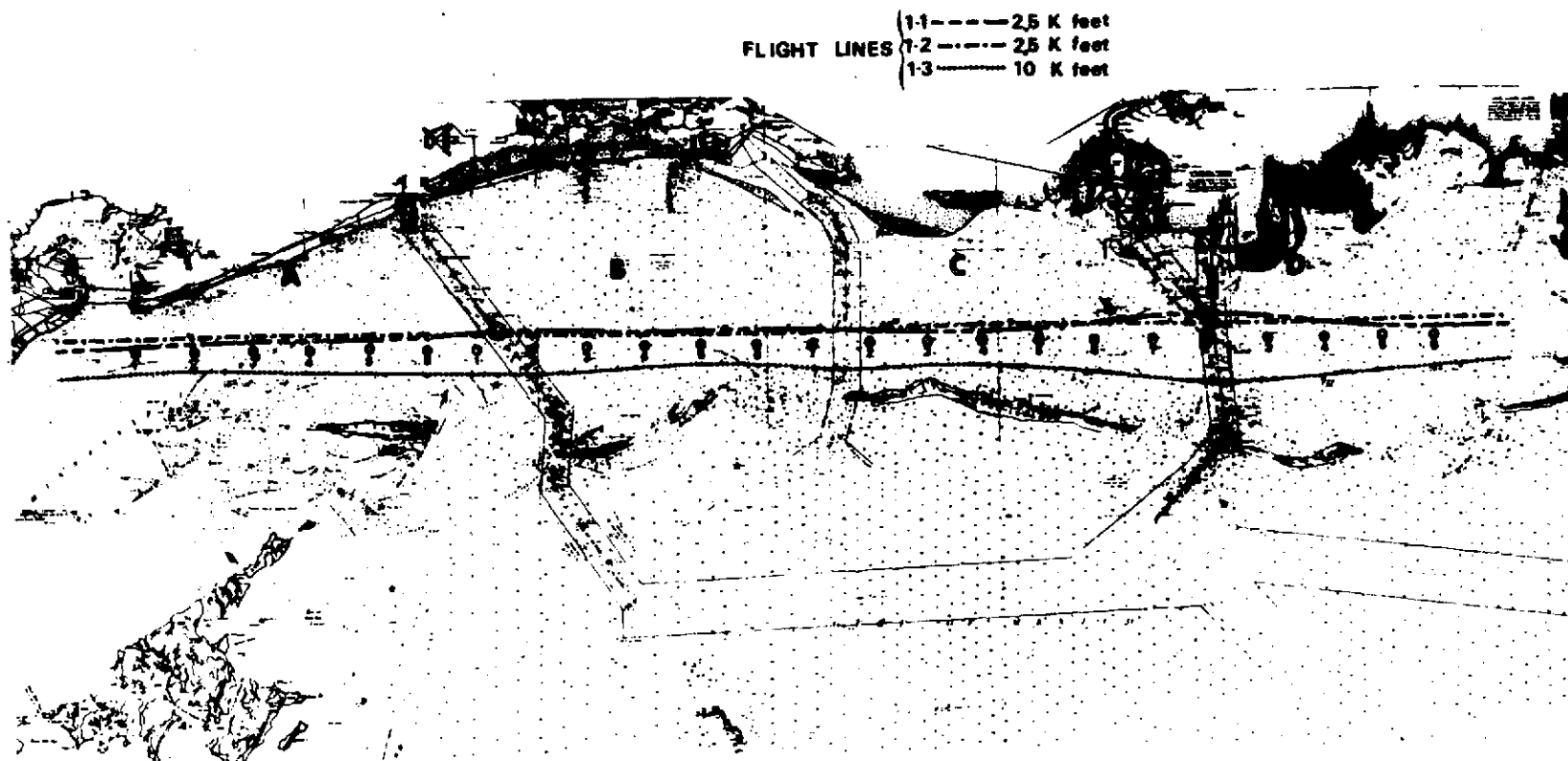


Figure 8 was produced using the spectral radiometer wavelength radiance versus time portion of the computer program mentioned in the previous section. Wavelengths at .54, .55, .56, .57, .58, .59 and .60 microns were selected for this plot. A comparison of the other wavelengths in the spectrum revealed a similar relationship between the two flight lines.

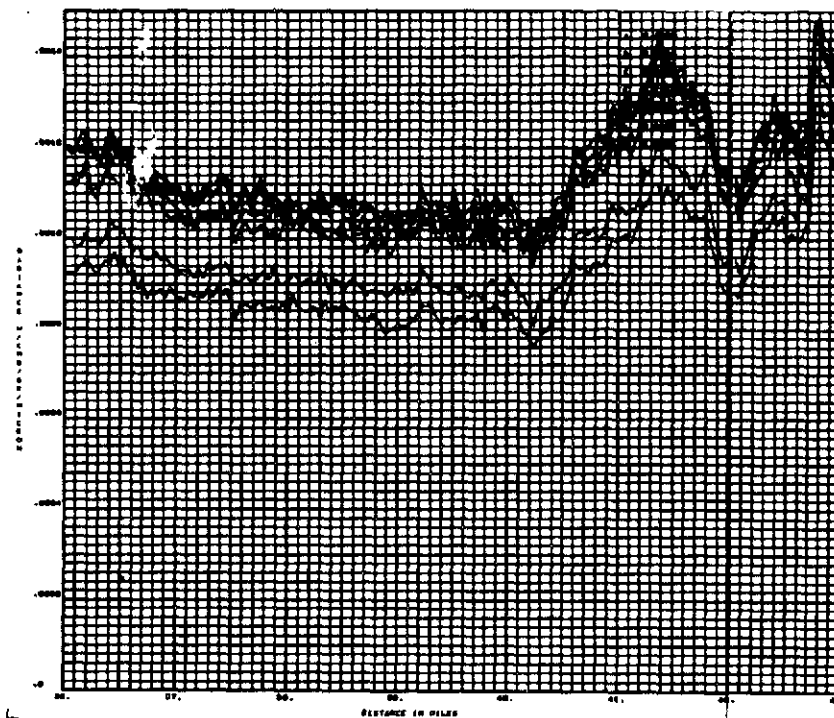
The shape of the backscattered radiance from the two flight lines is very similar, the main difference being in the absolute radiance values and the longitudinal scale. The change in radiance values between the two flights for a given location was approximately 12 to 13%. The primary cause of this increase in radiance in the second flight is attributed to the change in the apparent sun zenith angle. This angle changed from 66° to 63° . This resulted in a .26 reduction of the apparent optical air mass. Calculations showed that for the atmospheric conditions during this flight, the expected changes in radiance caused by the change in zenith angle should be approximately 11%. [These calculations were performed by Dr. R. Boudreau, ERL Atmospheric Group] This value is in agreement with the measured value of 12 to 13%. The remaining difference can probably be attributed to changes in the surface reflectivity or other variables (sun glint, polarization, atmospheric, etc.) which can affect the spectrum received by the spectral radiometer, or by actual changes in the water.

The longitudinal scale was based on the estimated ground speed of the aircraft. The inaccuracy in the estimated aircraft speed resulted in the different longitudinal scales.

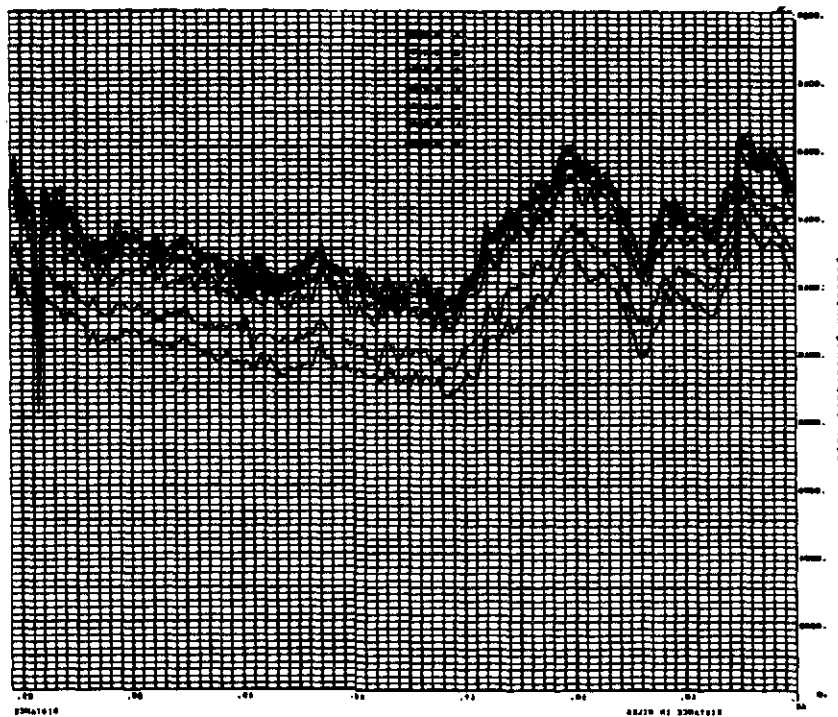
Effect of Altitude Variations

The two high altitude flight lines on the August 4, 1972 mission were flown at 10K feet. The spectral radiometer ground spot coverage at this altitude with a 180kts ground speed is approximately 304 feet in length by 131 feet in width

Figure 8. Wavelength vs Distance plots for August 4, 1972 Mission. Same location in Mississippi Sound on both Flight Lines



Flight Line 1-1, 2.8K feet



Flight Line 1-2, 2.5K feet

as compared to 236 feet in length by 33 feet in width for 2.8K feet altitude and 140kt air speed.

A comparison of the 2.8K feet and 10K feet flight lines for the same flight line area reveals the same characteristic shape. The small surface irregularities noted in the 2.8K feet flight line have been averaged out in the 10K feet lines because of the larger spectral radiometer foot print at 10K feet. The overall radiance level of the 10K feet flight line (Figure 9) is 100% larger over the visible band than the 2.8K feet flight line. Approximately 45% of this increase can be attributed to the decrease in sun zenith angle. A large percentage of the remaining increase can be attributed to "air light"; air light is direct sunlight, skylight and terrain reflected light that has been scattered by the air and by the particles in the air between the sea surface and the aircraft. [1] As the altitude increases, the area observed by the instrument increases, and the path length through the atmosphere increases and thus the amount of air light that can enter the instrument increases.

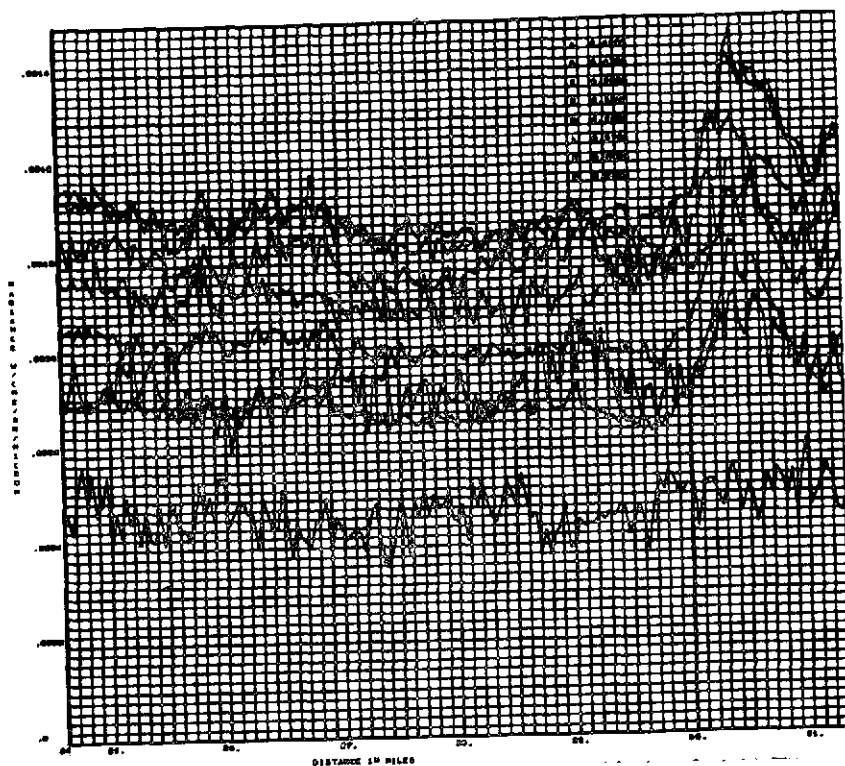
The increase in radiance at the high altitude was not uniform over the visible band. The shorter wavelength had a larger percentage increase. This increase is caused by the preferential scattering of the shorter wavelengths by the atmosphere.

Chlorophyll Determination

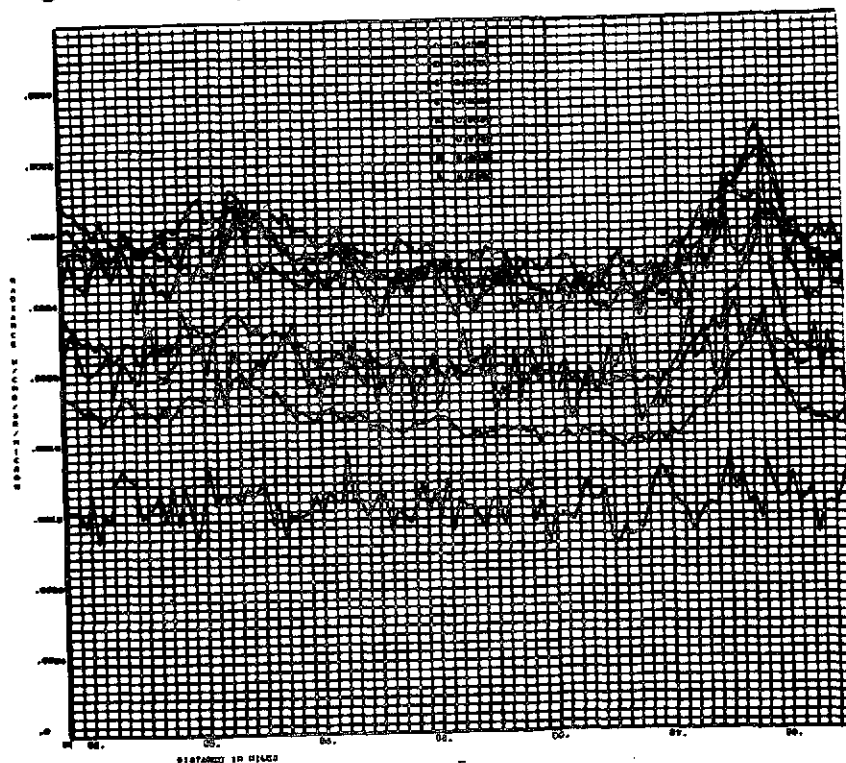
The objective of this phase in developing a method of determining chlorophyll concentration was to find wavelengths whose change in radiance values could be correlated with changes in sea truth chlorophyll.

Figure 10 is the spectral reflectance of two different areas of the Mississippi Sound flown at 2.5K feet. The sea truth for this area indicated a similar secchi visibility of 3.5 feet and 5 feet, but a chlorophyll value of 16.9mg/m^3 for one area and 2mg/m^3 for the other. An examination of the two curves reveals that the visible spectrum between 450nm and 650nm for the high

Figure 9. Spectra of backscattered light from the same area of the Mississippi Sound taken at 2.8K feet and 10K feet.



Flight Line 1-1, 2.8K feet



Flight Line 1-5, 10K feet

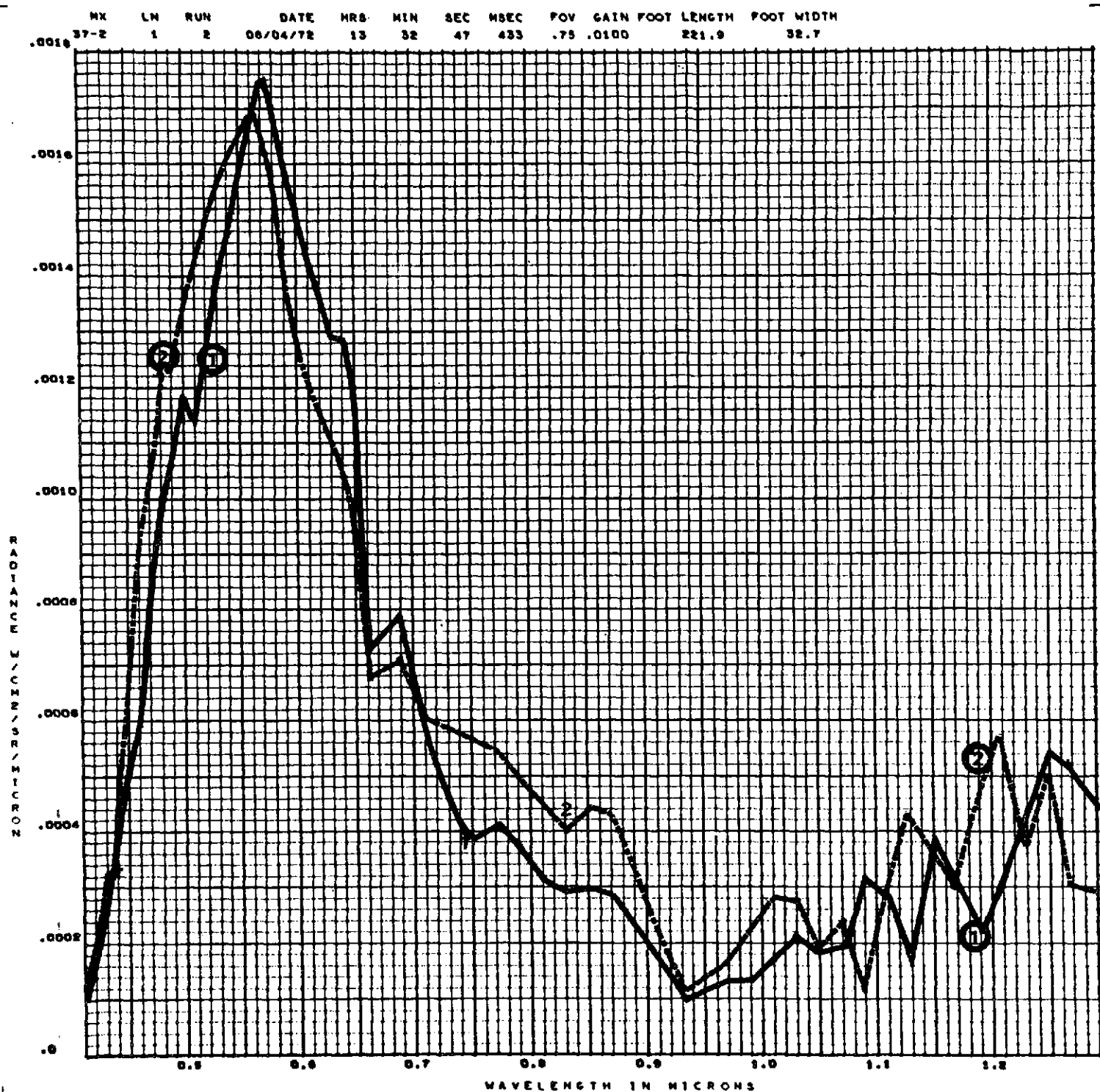


Figure 10. Spectra of backscattered light from the Mississippi Sound taken at 2.5K feet.

The first (1) Spectra was from an area which had a chlorophyll concentration of 16.9 mg/m^3 and the second (2) Spectra from an area with 2 mg/m^3 chlorophyll concentration.

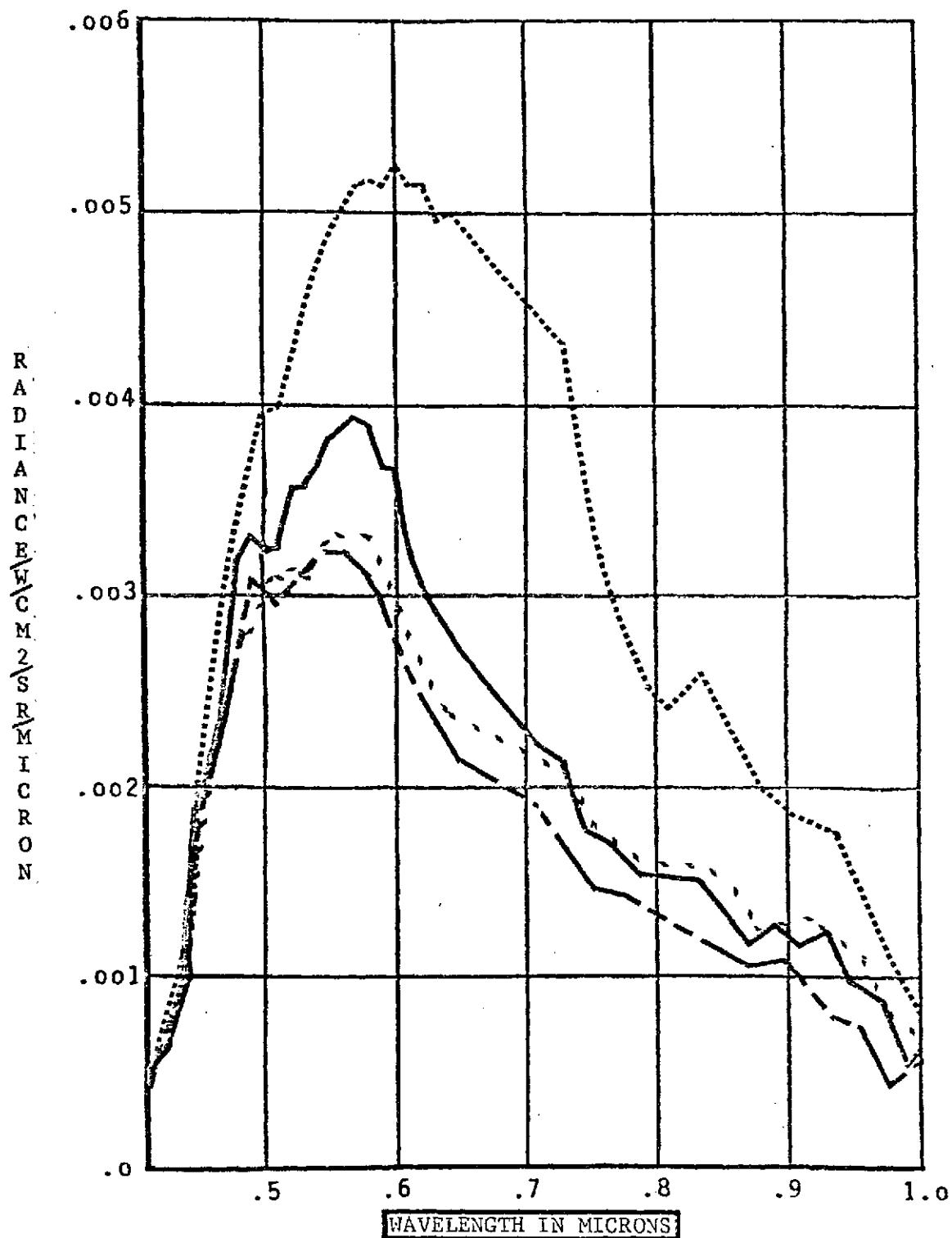
chlorophyll spectra has shifted toward the longer wavelengths with respect to the spectra with the lower chlorophyll content.

The radiance values for the two curves are identical at 560nm. The literature indicates, for oceanic waters, wavelengths around 520nm are not affected by changes in chlorophyll concentrations. [4] Assuming that the differences in chlorophyll concentrations are the primary factor which has caused the two curves to differ, then the wavelength which is ~~not~~ affected by chlorophyll has shifted from 520nm for oceanic waters to 560nm for very turbid waters.

The high chlorophyll radiance curves display a reduction in radiance values in the blue region of the spectra and an increase in radiance values in the orange to red region of the spectrum. This blue-red shift in the spectra is consistent with the results reported by Clarke, et al (1970) in their investigation of measuring chlorophyll concentration from aircraft.

The shift in the spectra observed in Figure 10 for chlorophyll changes is somewhat masked when there is also a large change in turbidity. Figure 11 is an example of how the spectra shifts and changes in amplitude for changes in chlorophyll and secchi visibility. These spectra are from the August 7, 1972 mission, Line C2.

The first spectra, which is nearer to shore, compared with the other three spectra is considerably larger in amplitude and has a general shift to the longer wavelengths. An examination of the second and third spectra indicates that the majority of the amplitude change is caused by the difference in secchi visibility, for the chlorophyll concentration at the location of these spectra curves is the same. However, a comparison of the third spectra with the fourth spectra indicates that secchi visibility is not the only factor affecting amplitude for both of these curves have the same secchi visibility but different amplitudes. The shift in wavelength as noted in Figure 10, also is found when



	Chlorophyll mg/m ³	SECCHI VISIBILITY FT.
..... 1 - 2 miles south of Deer Island	3.2	5
———— 2 - 1 mile north of Ship Island	1.4	8.5
- - - 3 - 1 mile south of Ship Island	1.4	14
- . - 4 - 1 mile north of Chandeleur Islands	1.1	14

Figure 11 - Spectra of backscattered light from the Mississippi Sound taken at 2.5K feet.

comparing the third and fourth spectra which have similar secchi visibility but different chlorophyll concentrations.

From the changes observed in Figure 10, several algorithms were tried in order to arrive at one which could be used to obtain chlorophyll concentrations based on the backscattered light received by the spectral radiometer.

The algorithm used in this initial phase was the radiance values at 620nm less the radiance values at 470nm divided by the radiance values at 520nm.

$\left[R = \frac{I_{620} - I_{470}}{I_{520}} \right]$ The 470nm value was selected because of sensitivity limitations of the detector that was installed in the spectral radiometer. The radiance values below 470nm were not considered useful. The detector has been replaced and radiance below 470nm should be useful in later tests. The literature indicates that for a variety of phytoplankton there is a maximum absorption in the blue at about 440nm due to chlorophyll. [8] The radiance at 520nm was used in this study to normalize the airborne data based on the information from the literature for oceanic type of water. However, as indicated in Figure 10 for turbid waters, 560nm may have been a better wavelength at which to perform this normalization. The radiance at 620nm was selected because of the large differences in radiance values at this wavelength for changes in chlorophyll concentration.

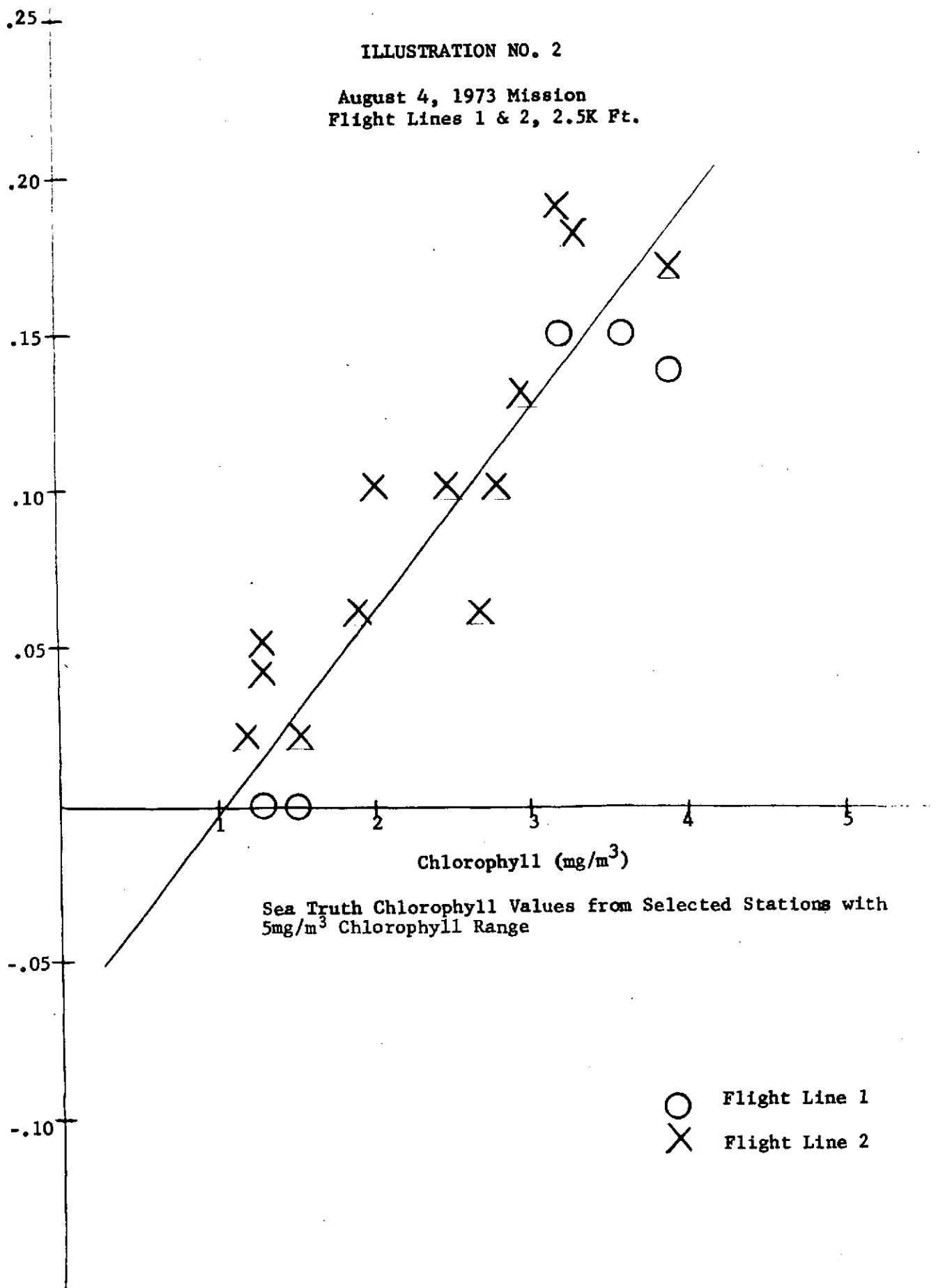
The chlorophyll algorithm was computed for the entire length of each flight line. The value of the algorithm at selected sea truth stations was plotted against chlorophyll values at the same locations. A straight line was drawn through the points. This line was then used in the conversion of all the values of the chlorophyll algorithm for the low altitude (2.5K ft.) flight lines into chlorophyll concentrations. (See Illustration No. 2)

A similar conversion chart was prepared for the high altitude flight lines using values of the algorithm derived from the high altitude spectral radiometer data. The low altitude chart (Illustration 2) could not be used to convert the high altitude algorithm value to chlorophyll concentration

ILLUSTRATION NO. 2

August 4, 1973 Mission
Flight Lines 1 & 2, 2.5K Ft.

$$R = \frac{1.620\mu\text{m} - 1.470\mu\text{m}}{1.520\mu\text{m}}$$



because the blue region of the spectra had a large increase in radiance as a result of increased atmospheric scattering in this region of the spectra. This caused the algorithm ratio to be smaller for high altitude data than for low altitude data for the same value of chlorophyll concentration.

Figure 14 is a summary of the chlorophyll algorithm ratio with respect to the sea truth chlorophyll value at each sea truth station for low altitude flight lines. This figure was plotted similar to Illustration 2. However, values above 5mg/m^3 were also included in this summary.

During this phase of the investigation the computer program that was used to plot the algorithm values for chlorophyll concentration used a linear relationship for the change in spectral signature (algorithm value) and the sea truth chlorophyll concentration. A review of Figure 14 indicates that this relationship is not linear especially for values of chlorophyll above 5mg/m^3 .

This non-linear relationship is therefore evident in the following chlorophyll plots for the July 24, August 4 and August 7 missions.

The chlorophyll values for the October 18, 1972 mission were not plotted along the first flight lines because of the limited number of sea truth collection stations overflowed by the aircraft. However, a few points were included in Figure 14 to give an indication of how the algorithm reacted to high values of chlorophyll.

Sea Truth and Airborne Derived Chlorophyll Plots

July 24, 1972 Mission (See Figure 12)

Figures 15 and 16 are plots of the sea truth chlorophyll values for the 2.5K ft. airborne data derived from the chlorophyll algorithm. Two sea truth samples collected at each station at different times. The times between samples varied up to three hours. The difference in the sea truth chlorophyll value can likely be attributed to the very dynamic nature of the Mississippi

FIGURE 12 ERL BEECH AIRCRAFT FLIGHT LINES, 24 JULY 1972 MISSION, MISSISSIPPI SOUND

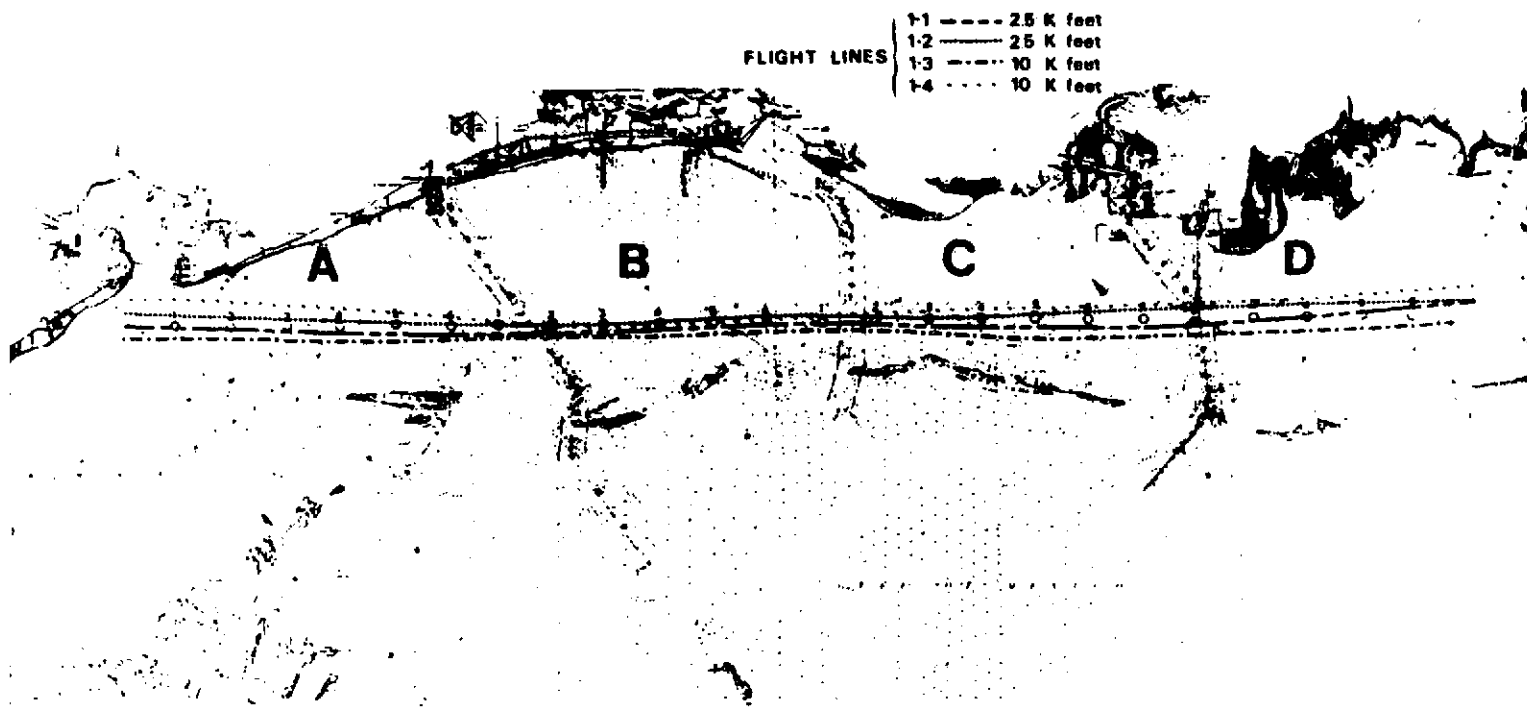


FIGURE 13. ERL BEECH AIRCRAFT FLIGHT LINES, 7 AUGUST 1972 MISSION MISSISSIPPI SOUND

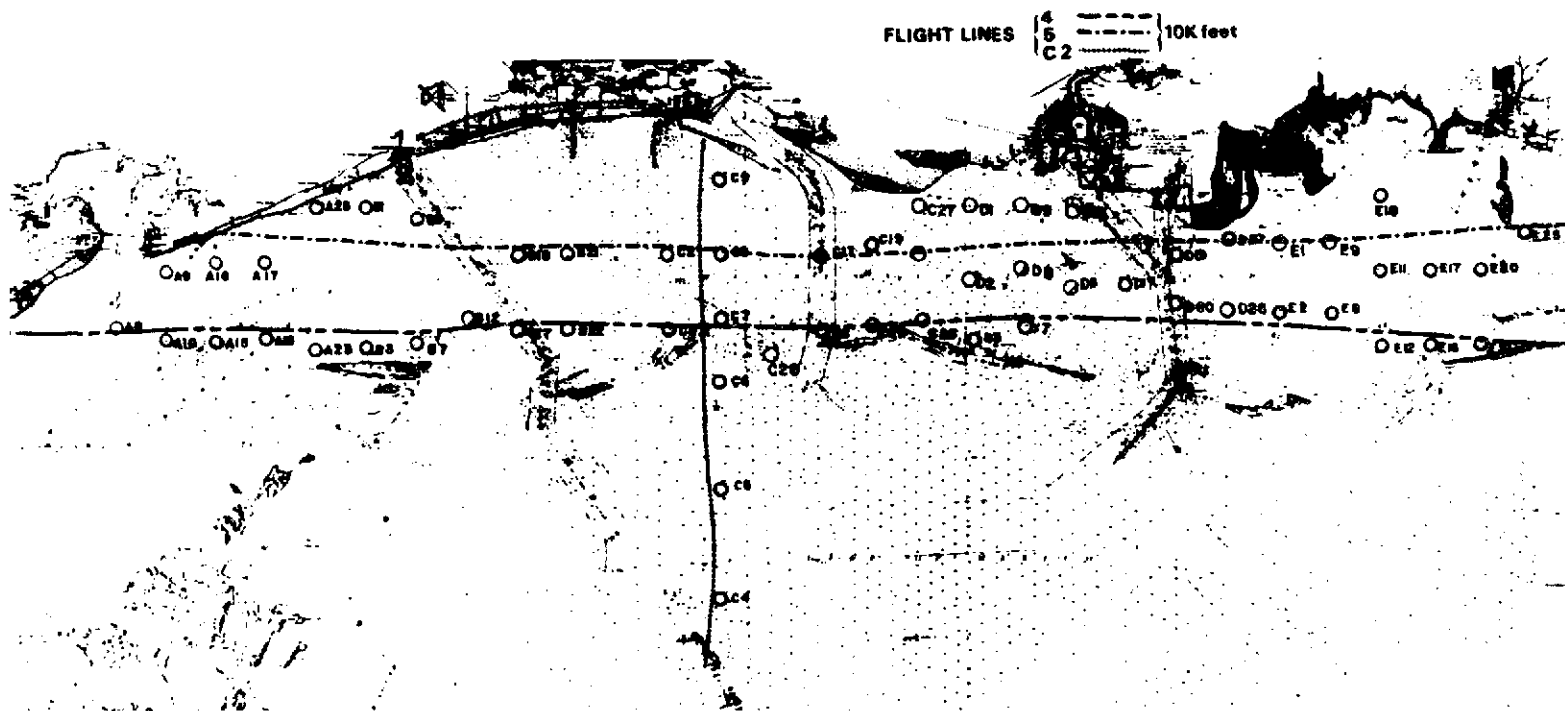
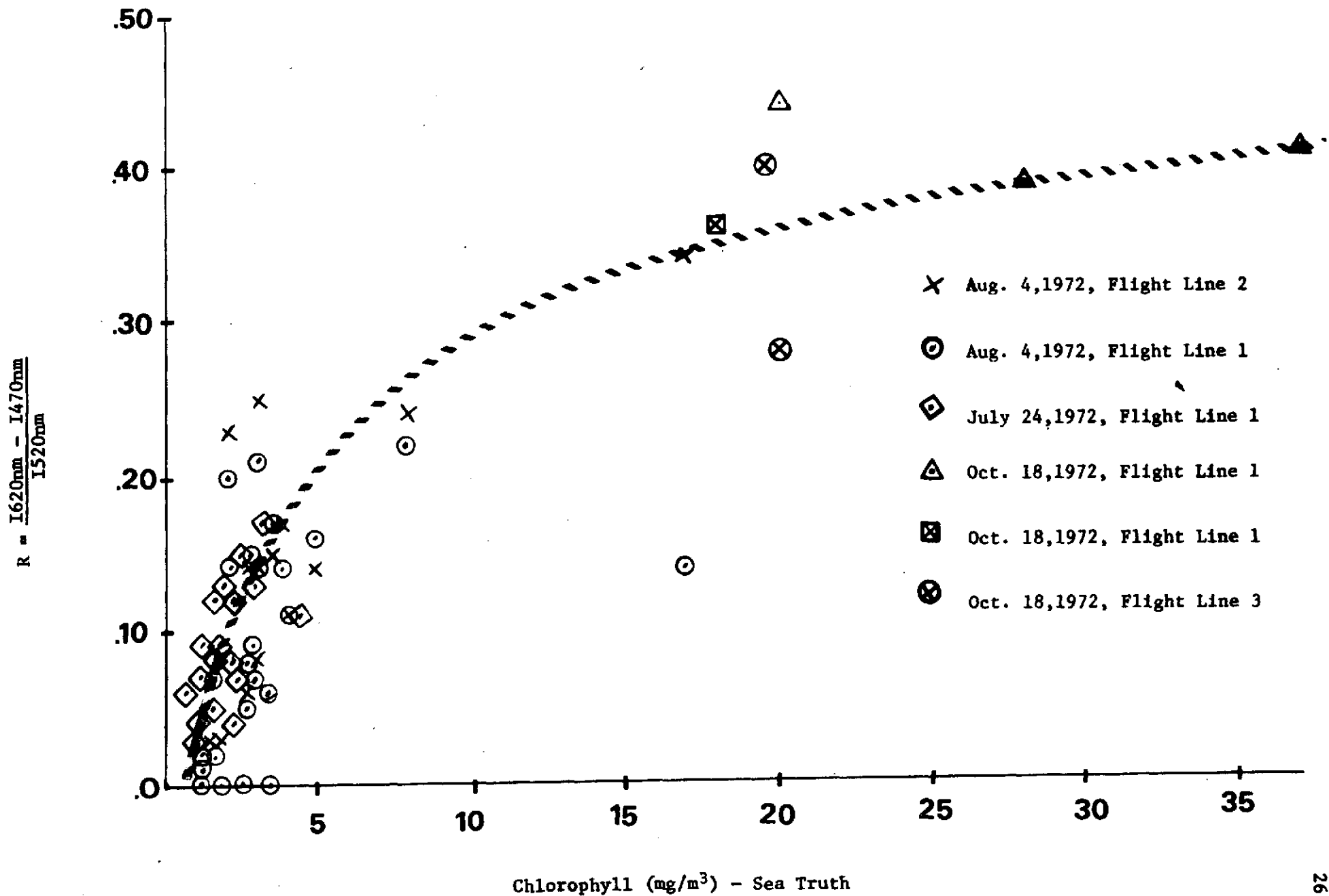


Figure 14. All low altitude chlorophyll data at sea truth station locations
from
The E-20D Spectral Radiometer



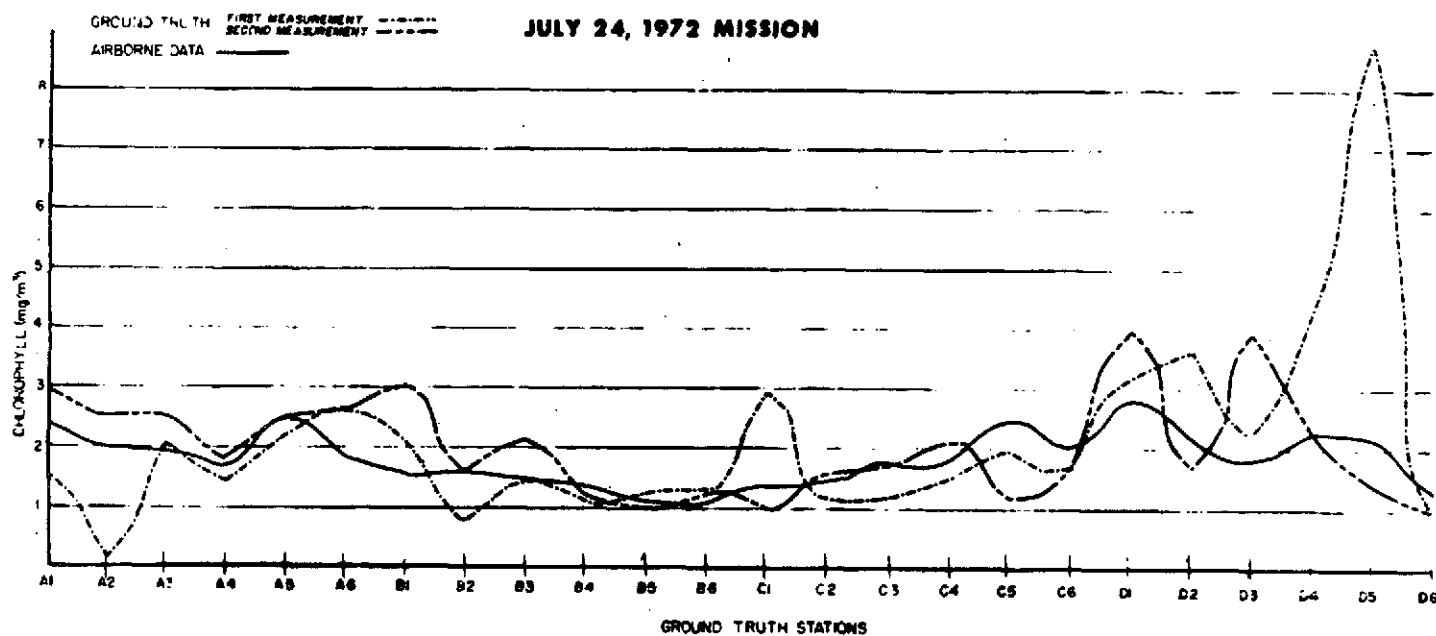
Sound. At some stations, both measurements were collected after the aircraft overflight. The two airborne derived chlorophyll values from the two flight lines (Runs 1-1, 1-2) compare very favorably with the sea truth except for the high peak in area D1.

Figures 17 and 18 are the corresponding 10K feet flight lines for this mission. In Figure 17 the airborne chlorophyll data is lower than the sea truth chlorophyll data. This flight line was flown farther out from the sea truth stations than originally intended. Since the chlorophyll concentration generally decreases as you go farther away from the shore, the airborne data may be an accurate representation of the chlorophyll concentration. In Figure 18 the chlorophyll concentration is higher for stations A1, A2, A3 and A4 than for the same stations in Figure 17. A review of Figure 12 indicates that flight lines 1-4 were flown much closer to the shore (with respect to the sea truth stations) than flight lines 1-3 in the area of the above sea truth stations. This increase in the airborne chlorophyll concentration over the sea truth chlorophyll concentration could be correctly revealing a higher chlorophyll concentration near the shore.

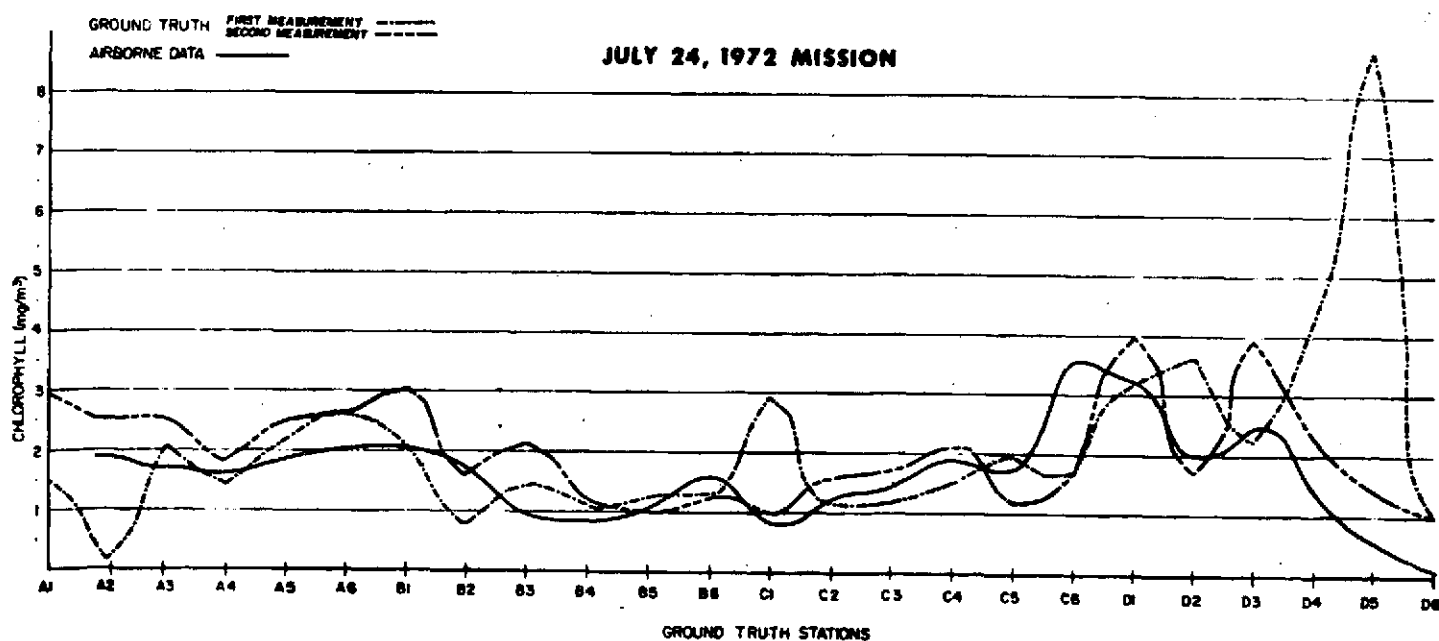
August 4, 1972 Mission (See Figure 7)

There is only one set of sea truth measurements for this mission. Figures 19 and 20 show the data plots for the 2.5K feet flight lines. The non-linearity of the chlorophyll radiance relationship for high values of chlorophyll is evident in these plots. In Figure 9 the aircraft flight line and the sea truth stations nearly coincided. This resulted in a good airborne representation of the chlorophyll concentrations.

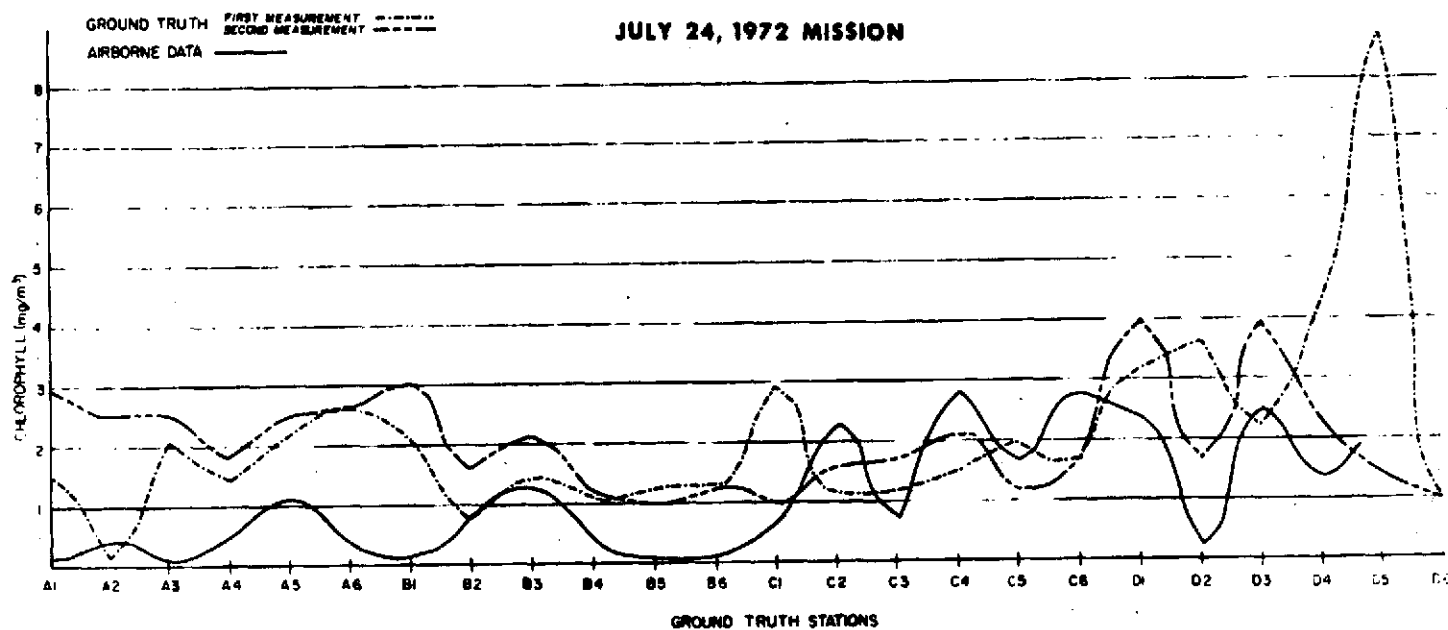
In the high altitude flight line, Figure 21, the airborne data is consistently lower in values than the sea truth data. This could be caused by flight lines being flown considerably farther out in the Sound than the line



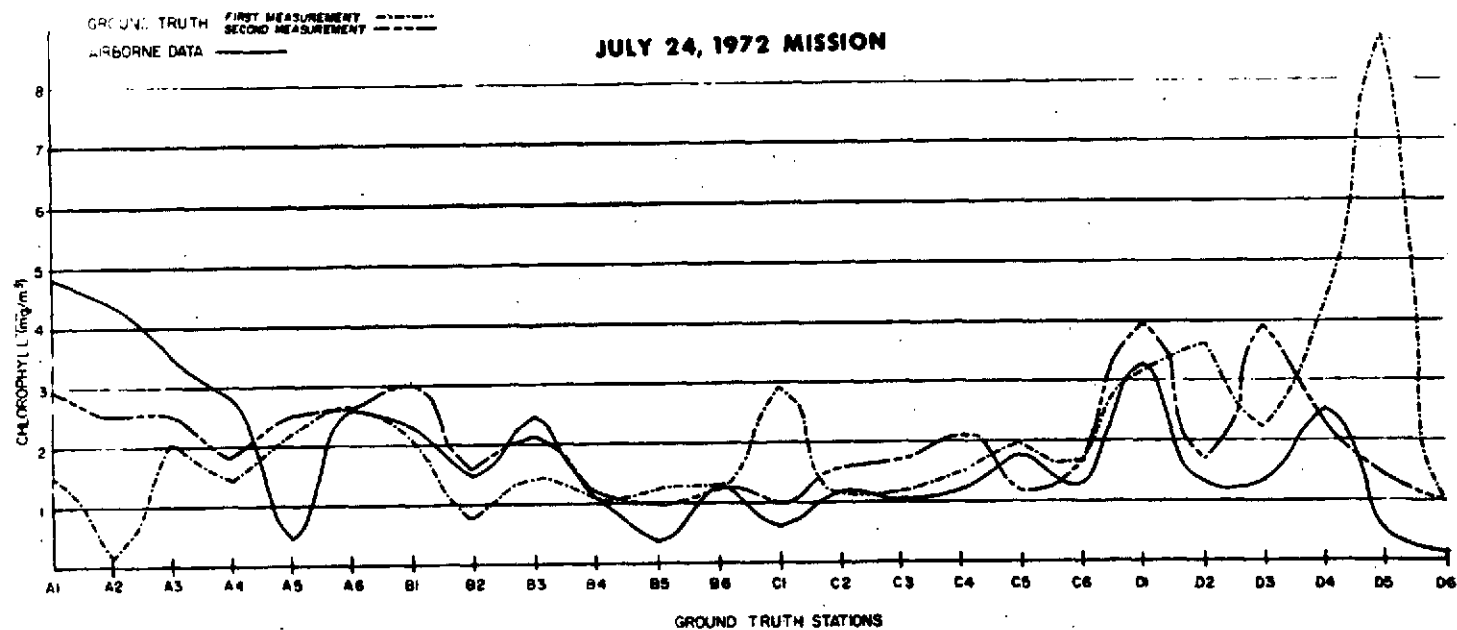
**FIGURE 15 AIRBORNE CALCULATED CHLOROPHYLL VALUES VS SEA TRUTH CHLOROPHYLL VALUES
FOR RUN 1-1, 2.5K FEET**



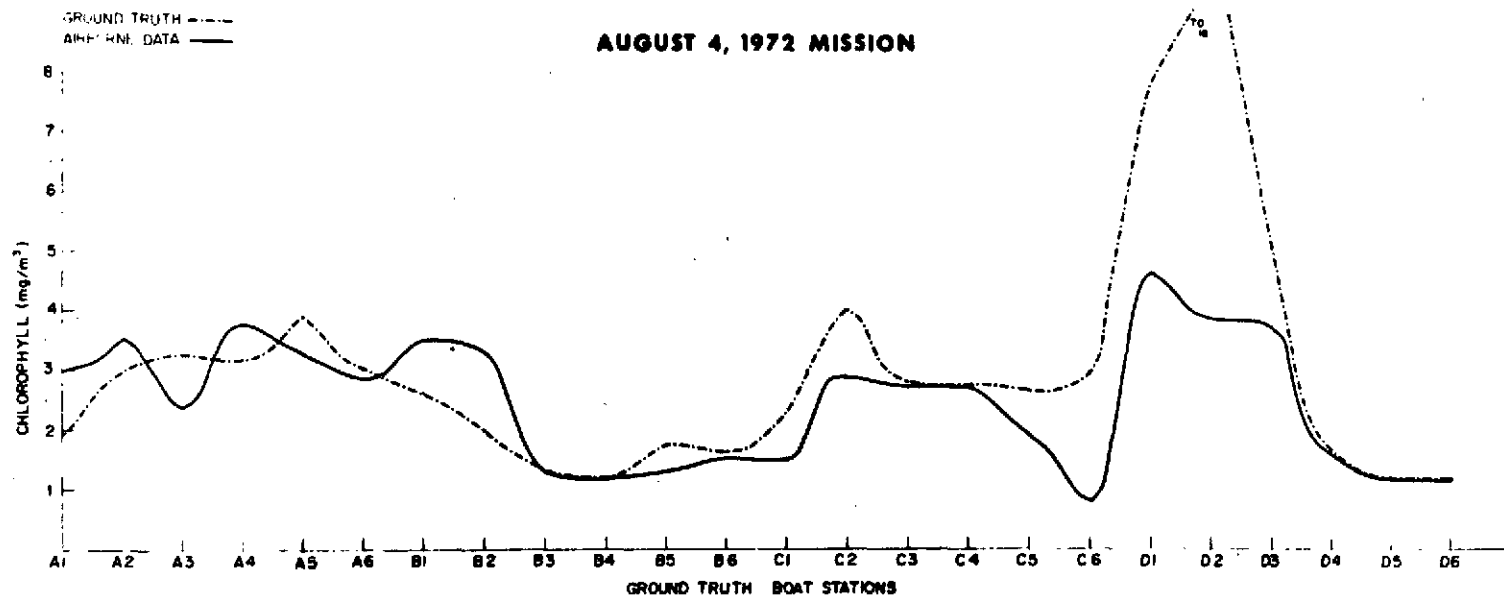
**FIGURE 16 AIRBORNE CALCULATED CHLOROPHYLL VALUES VS SEA TRUTH CHLOROPHYLL VALUES
FOR RUN 1-2, 2.5K FEET**



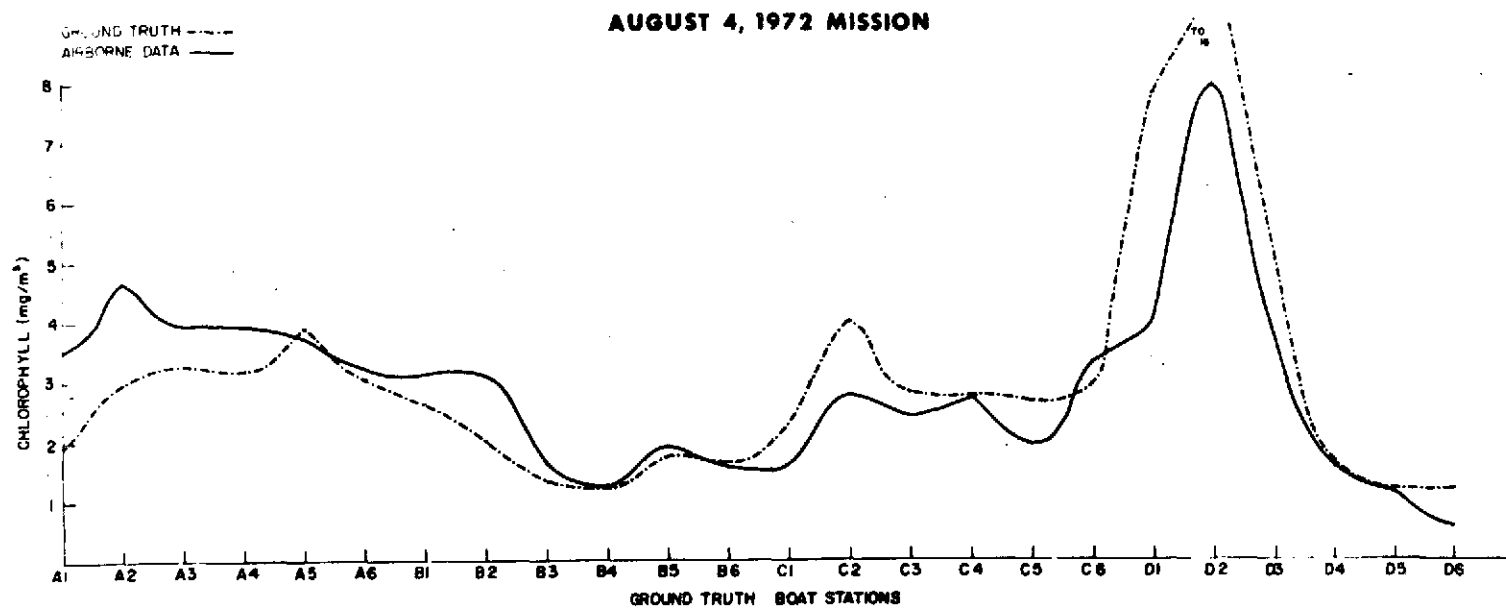
**FIGURE 17 AIRBORNE CALCULATED CHLOROPHYLL VALUES VS SEA TRUTH CHLOROPHYLL VALUES
FOR RUN 1-3 10K FEET**



**FIGURE 18 AIRBORNE CALCULATED CHLOROPHYLL VALUES VS SEA TRUTH CHLOROPHYLL VALUES
FOR RUN 1-4, 10K FEET**



**FIGURE 19 AIRBORNE CALCULATED CHLOROPHYLL VALUES VS SEA TRUTH CHLOROPHYLL VALUES
FOR RUN 1-1, 2.5K FEET**



**FIGURE 20 AIRBORNE CALCULATED CHLOROPHYLL VALUES VS SEA TRUTH CHLOROPHYLL VALUES
FOR RUN 1-2, 2.5K FEET**

of sea truth stations. The chlorophyll peaks at C2 and D2 did not show up at all in the airborne data. These peaks may have been small patches of high chlorophyll and did not extend out to the area overflown by the aircraft.

August 7, 1972 Mission

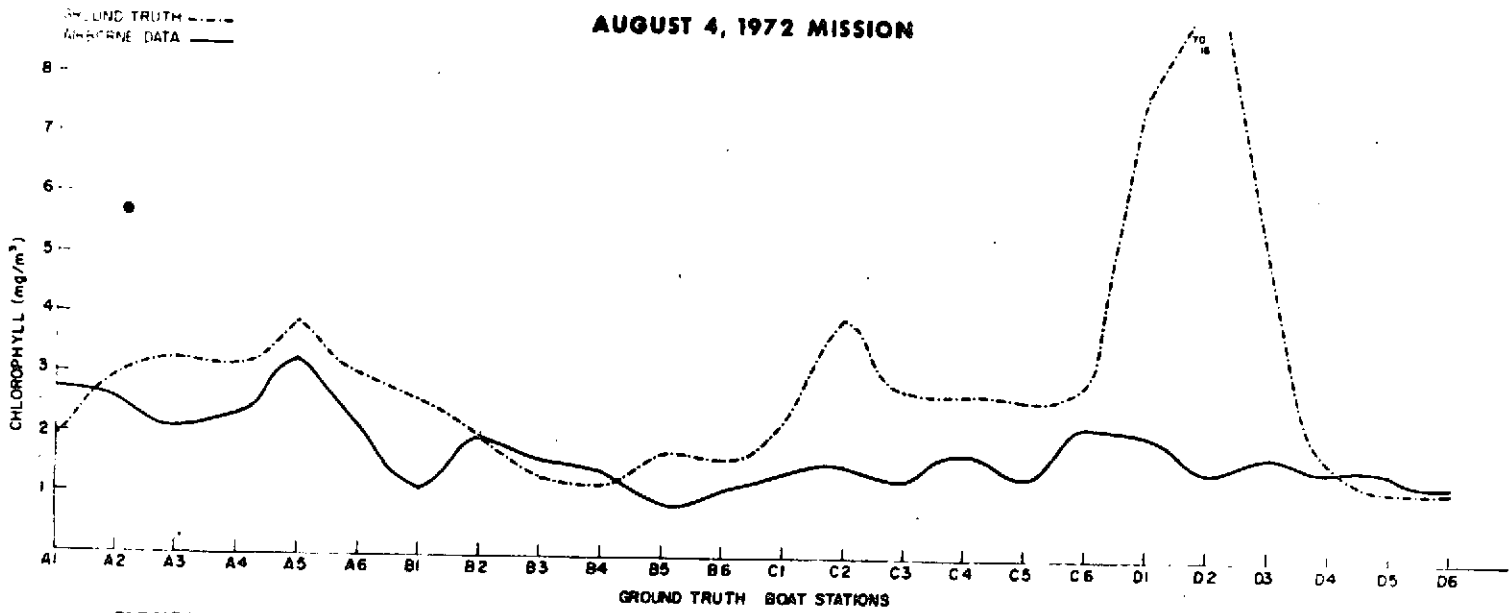
Three flight lines from this mission were processed. Two flight lines were lengthwise down the middle of the Sound and the third was a short north/south line east of Biloxi Bay (Figure 13). All the flight lines were flown at 10K feet.

Figures 22, 23 and 24 are plotted values of airborne and sea truth chlorophyll concentrations. The correlation of this 10K foot airborne chlorophyll data for this mission is considerably better than the two previous missions except that the problem of non-linearity for high values of chlorophyll is still present. This improvement in the airborne data can probably be attributed to the good meteorological conditions experienced during the mission. The sky was clear of haze and the Mississippi Test Facility radiosonde indicated a lower water vapor content than the other two missions. This resulted in a less pronounced increase in the radiance values in the blue region.

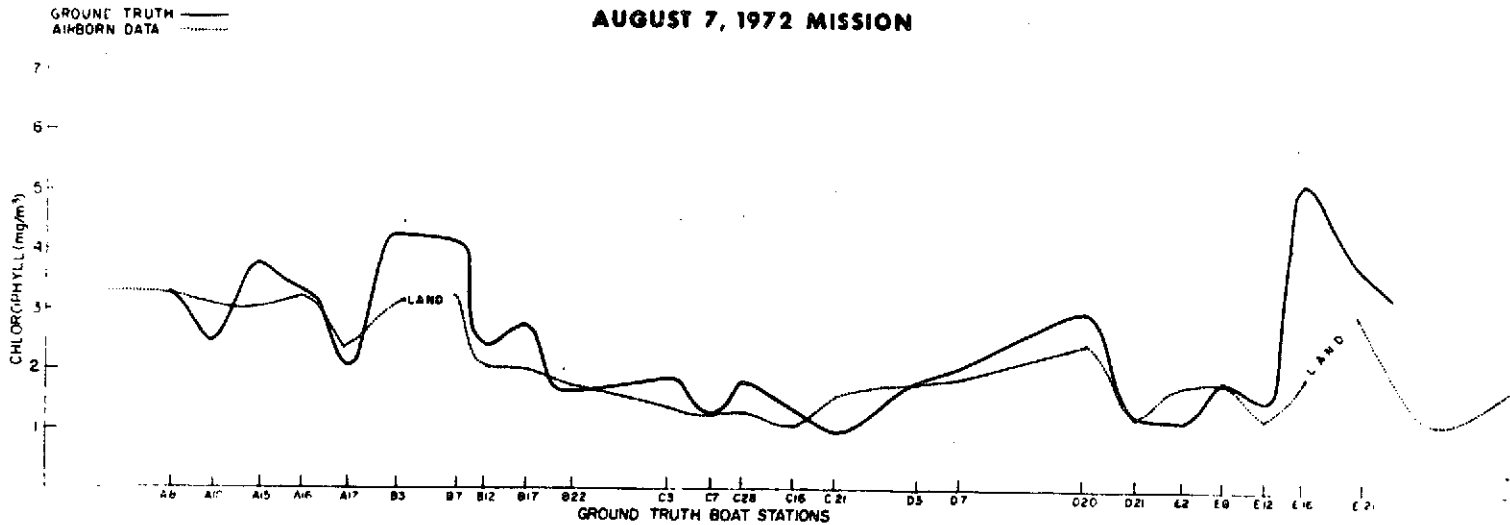
Figure 24 illustrates the decrease in chlorophyll concentrations as you go farther out in the Sound from the shore. Station C9 is the sea truth station closer to shore with stations C8 and C7 located in the Sound and stations C6, C5 and C4 located outside the Sound in the Gulf.

SECCHI VISIBILITY

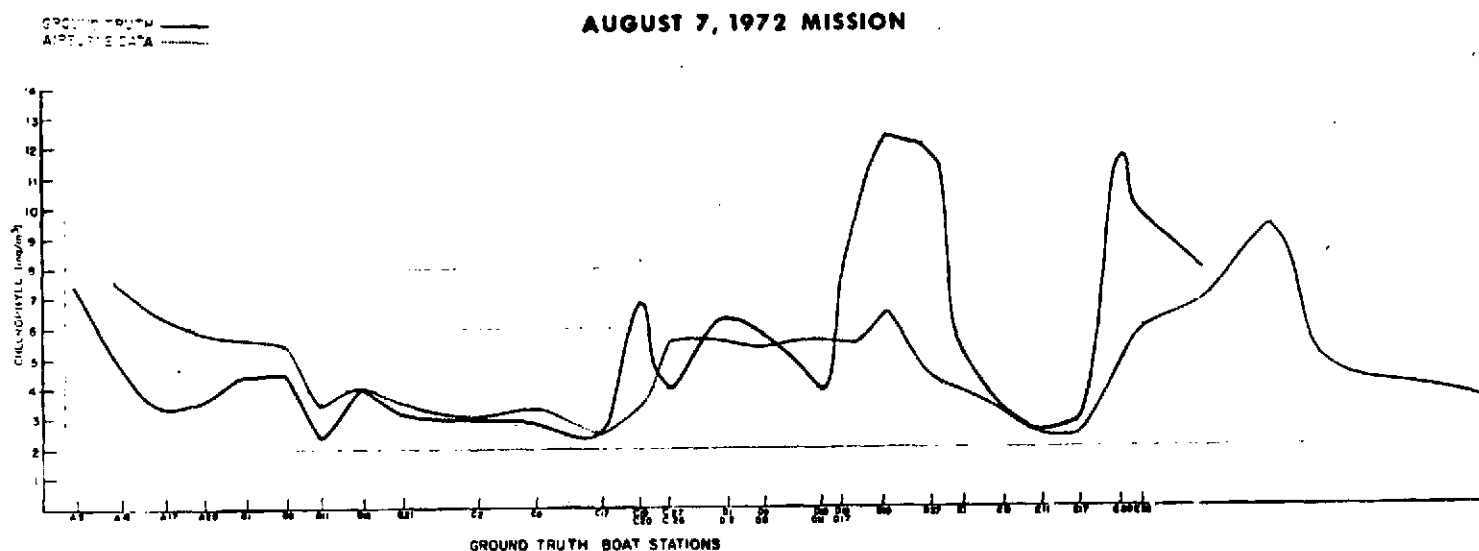
Besides chlorophyll, turbidity is a parameter that one would like to measure by remote sensing methods. Secchi visibility is the surface measurement that will be used as an indication of turbidity. Whether or not secchi visibility is a good indicator of turbidity was not addressed in this investigation.



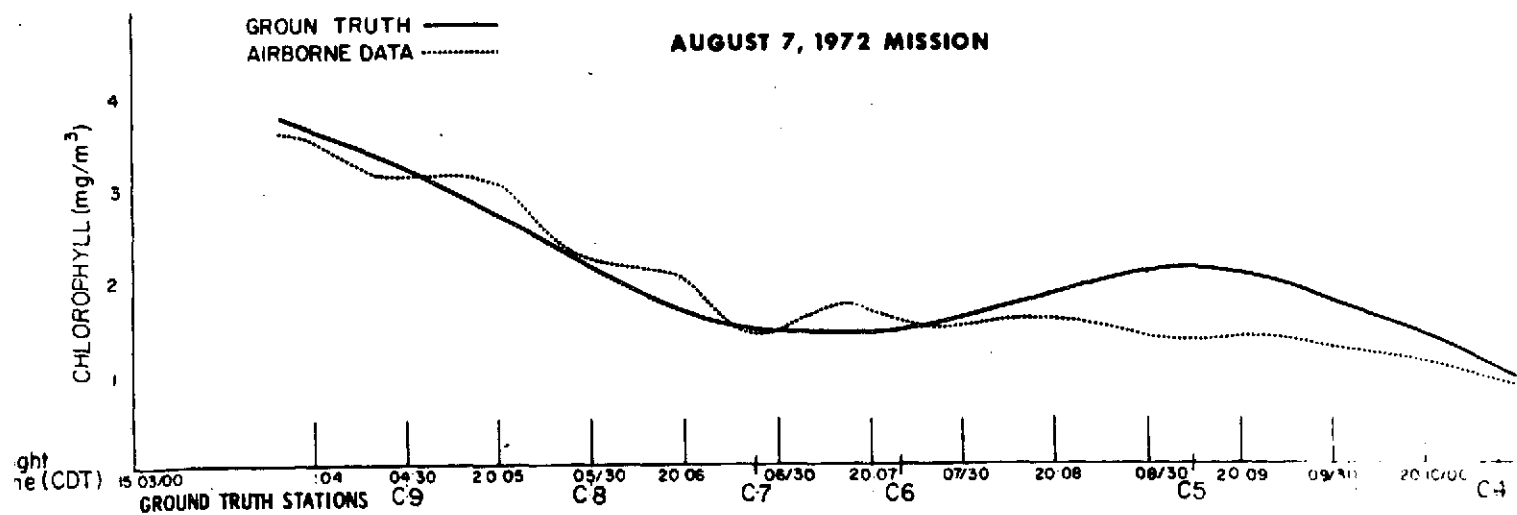
**FIGURE 21 AIRBORNE CALCULATED CHLOROPHYLL VALUES VS SEA TRUTH CHLOROPHYLL VALUES
FOR RUN 1-3, 10K FEET**



**FIGURE 22 AIRBORNE CALCULATED CHLOROPHYLL VALUES VS SEA TRUTH CHLOROPHYLL VALUES
FOR LINE 4, 10K FEET**



**FIGURE 23 AIRBORNE CALCULATED CHLOROPHYLL VALUES VS SEA TRUTH CHLOROPHYLL VALUES
FOR LINE 5, 10K FEET**



**FIGURE 24 AIRBORNE CALCULATED CHLOROPHYLL VALUES VS SEA TRUTH CHLOROPHYLL VALUES
FOR LINE C2, 10K FEET**

Several different algorithms were tried in order to find an expression which would correlate the radiance data from the spectral radiometer with secchi visibility. The ratio of the radiance at 550nm to 600nm was selected as giving a reasonable ratio which could be correlated to secchi visibility. $R = \frac{I_{550}}{I_{600}}$

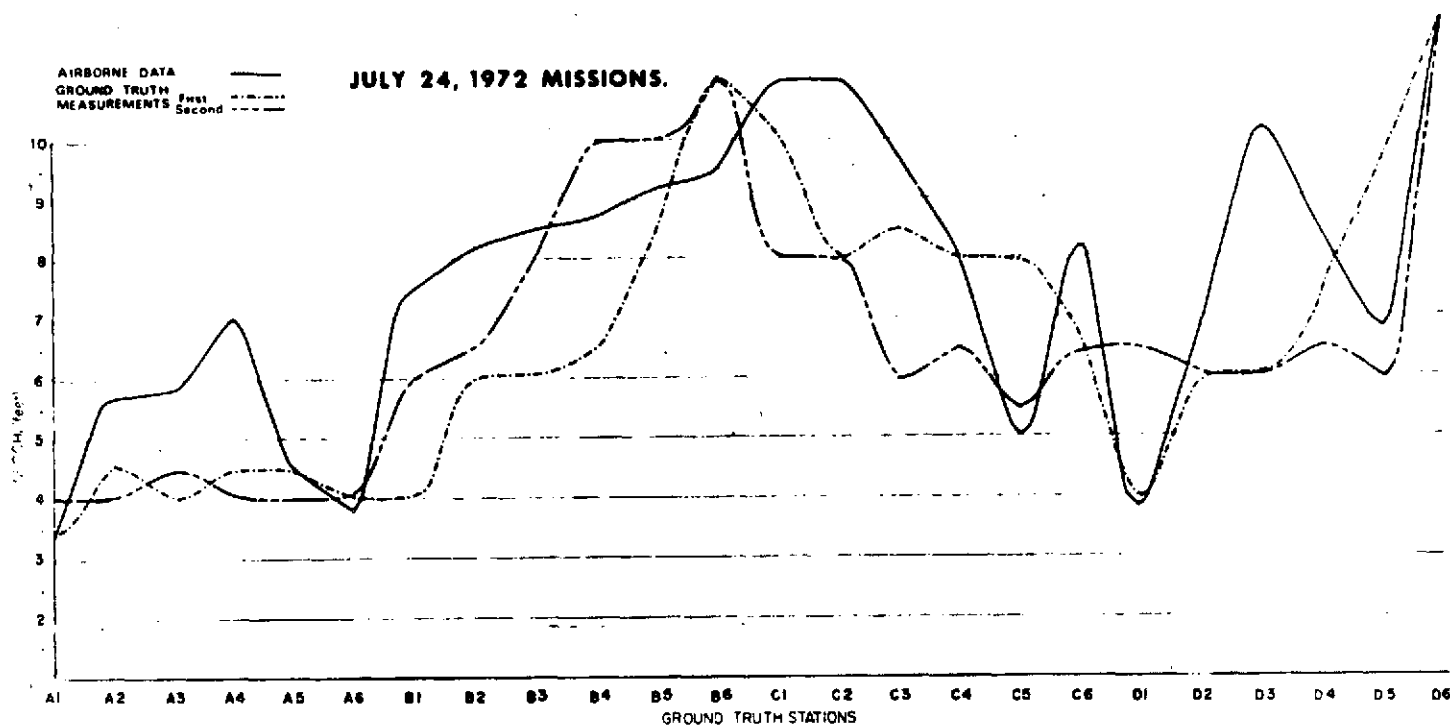
A linear calibration was made to the ratio between two sea truth calibration points. The two calibration points were selected so that the secchi visibility differed substantially in value. It was assumed that the secchi visibility varied linearly with changes in the radiance ratio between the two calibration points. A different calibration scale was used for each flight line.

July 24, 1972 Mission

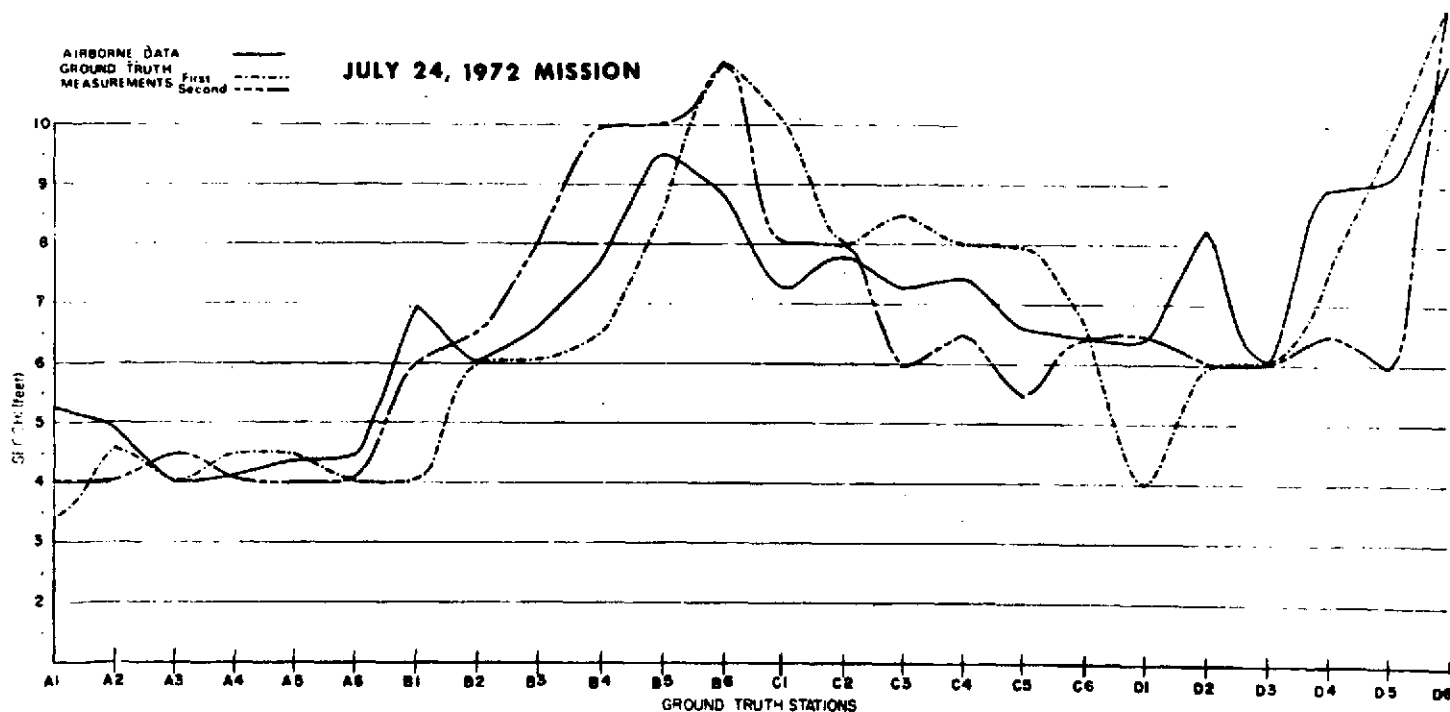
The surface and remote secchi visibility measurement values obtained during this mission are shown in Figures 25 and 26. The correlation between remote and surface are generally good; however, there are areas such as around stations A2 thru A5 and D2 thru D4 on Line 1-1 where the remote values are 3 to 4 feet greater. On line 1-2, Figure 26, the airborne data stayed within the two sea truth values for a larger portion of the flight line than for flight line 1-1. The reason for these deviations between airborne and surface data is not known.

August 4, 1972 Mission

Examples of remote and surface secchi visibility measurements obtained during the August 4, 1972 mission are shown in Figures 27, 28 and 29. The airborne data follows the same trend as the surface data but there are considerable quantitative differences between the airborne and surface measurements at a few stations. The increase in altitudes, Figure 29, causes a larger number of stations where there are considerable differences between the sea truth values and the airborne derived data.



**FIGURE 25 AIRBORNE CALCULATED SECCHI VISIBILITY VALUES VS SEA TRUTH SECCHI VISIBILITY VALUES
FOR LINE 1-1, 2.5K FEET**



**FIGURE 26 AIRBORNE CALCULATED SECCHI VISIBILITY VALUES VS SEA TRUTH SECCHI VISIBILITY VALUES
FOR LINE 1-2, 2.5K FEET**

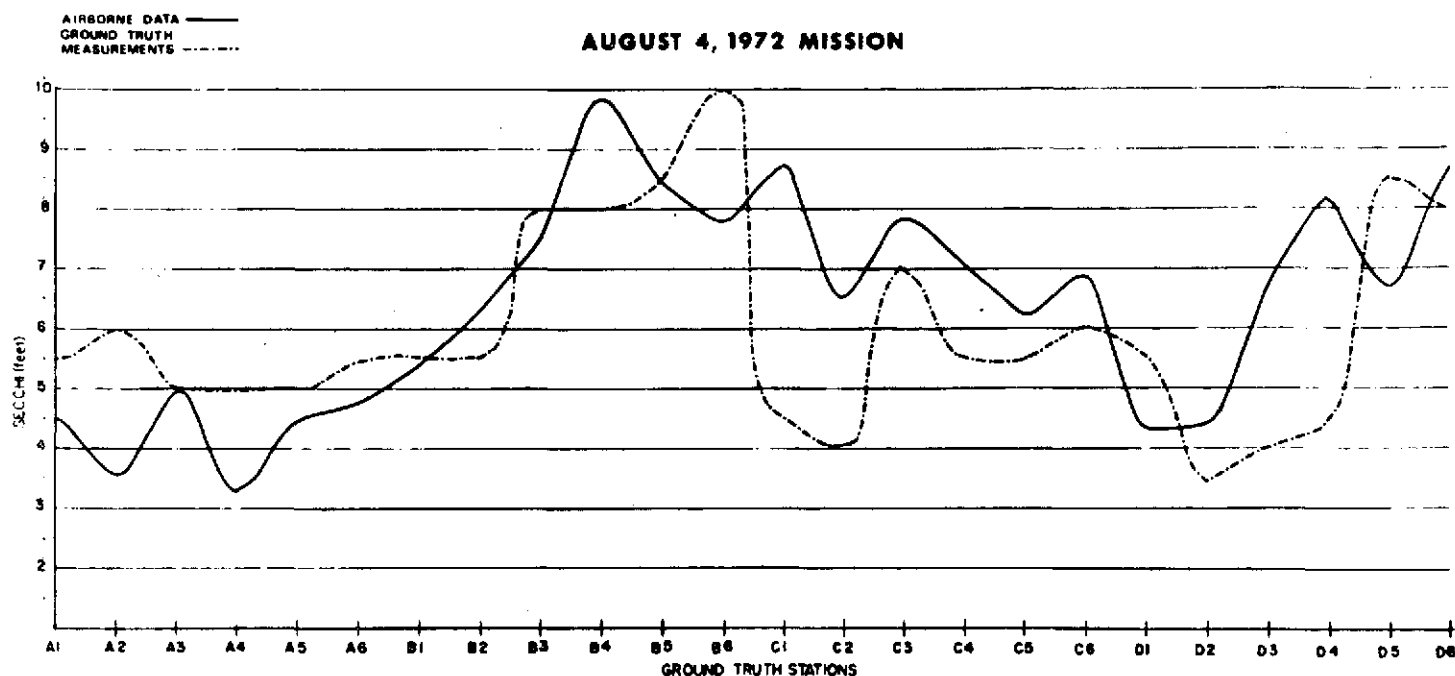


FIGURE 27 AIRBORNE CALCULATED SECCHI VISIBILITY VALUES VS SEA TRUTH SECCHI VISIBILITY VALUES FOR LINE 1-1, 2.5K FEET

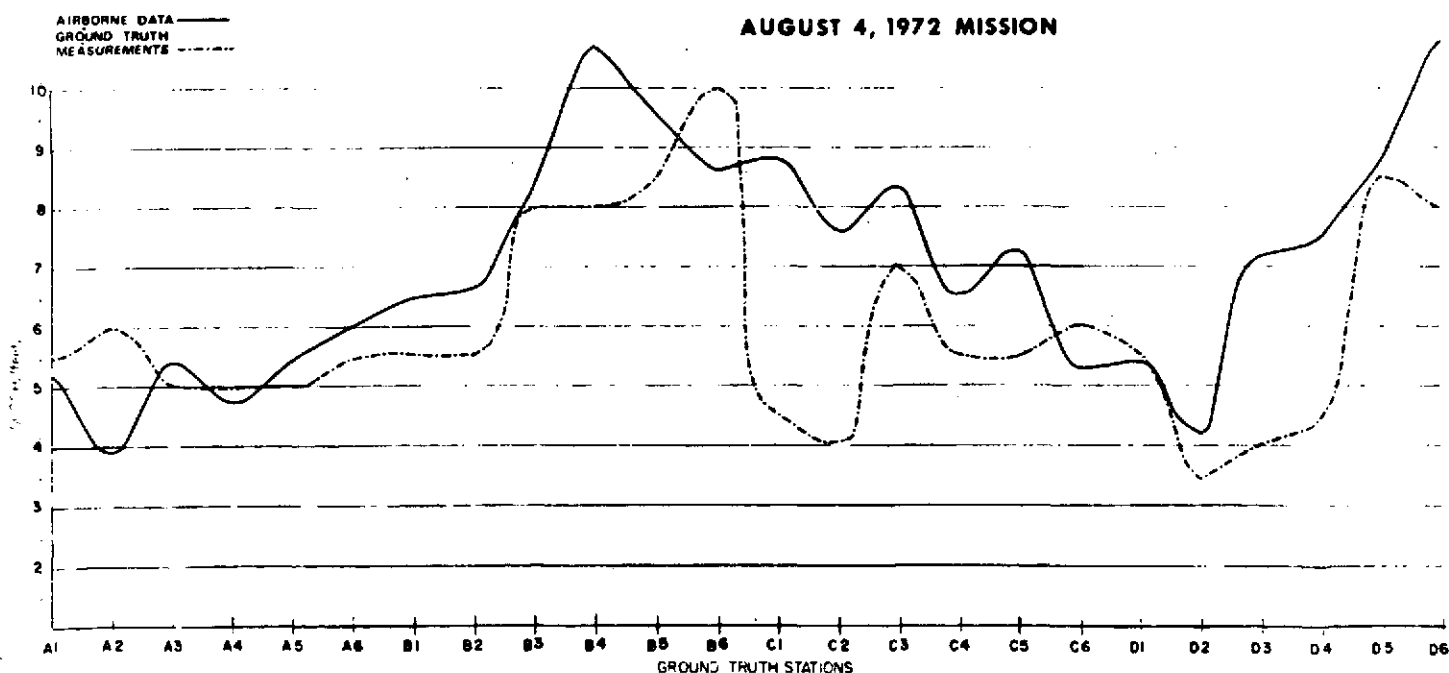
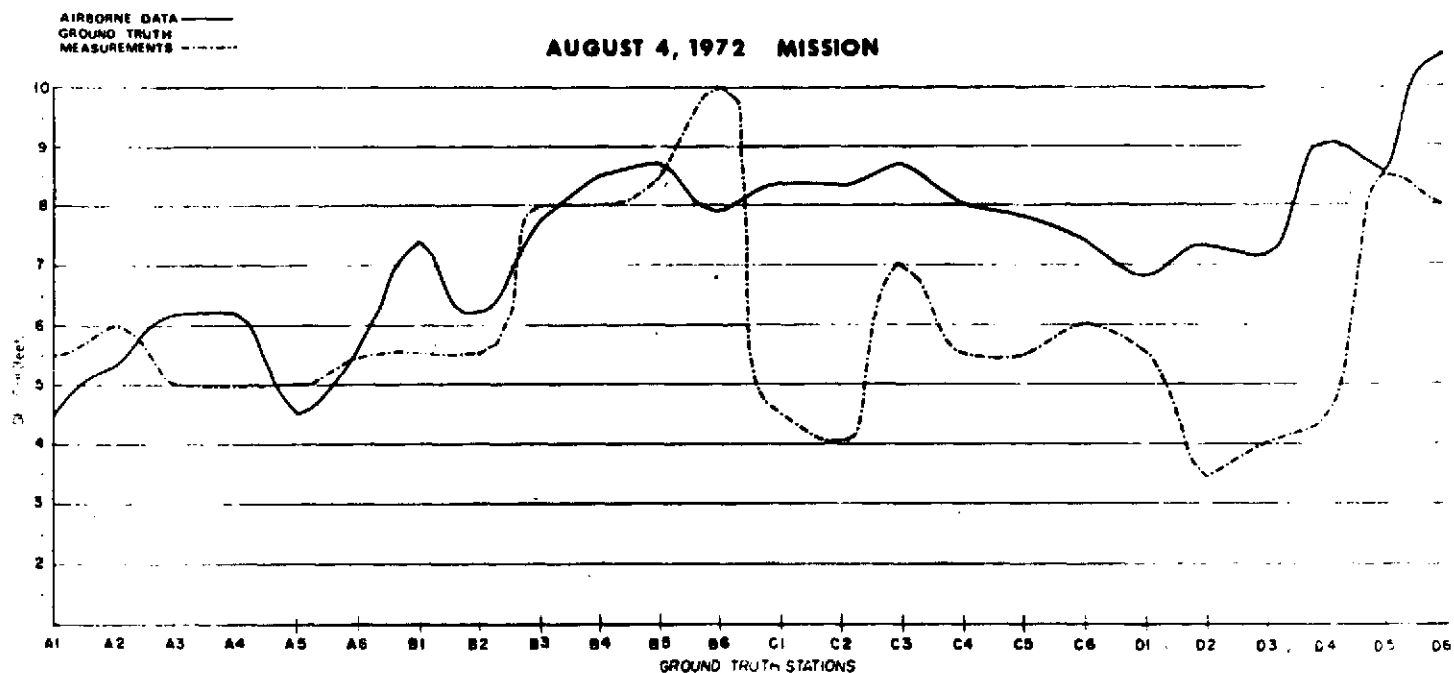


FIGURE 28 AIRBORNE CALCULATED SECCHI VISIBILITY VALUES VS SEA TRUTH SECCHI VISIBILITY VALUES FOR LINE 1-2, 2.5K FEET

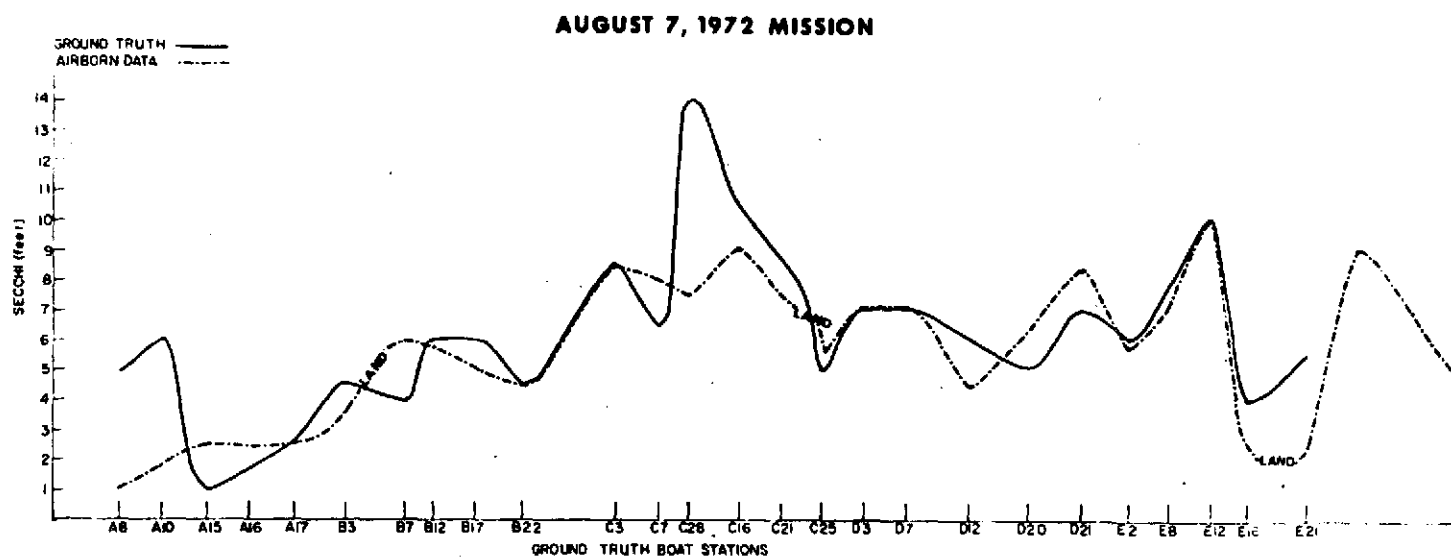
August 7, 1972 Mission

Examples of remote and surface secchi visibility measurements obtained during the August 7, 1972 mission are plotted in Figures 30, 31 and 32. All of these flight lines were flown at 10K feet.

This mission produced some of the best correlation between secchi airborne and surface data. Whether the clear sky condition during the mission or the improvement in the sea truth sampling time and location with respect to aircraft overflight was responsible for the improvement in the data is not known. The large number of sea truth measurements collected during the mission did allow an interpolation of sea truth measurements to be used when the aircraft did not directly overfly a measurement station. This was not possible with the other two missions because of the limited number of sea truth measurements obtained.



**FIGURE 29 AIRBORNE CALCULATED SECCHI VISIBILITY VALUES VS SEA TRUTH SECCHI VISIBILITY VALUES
FOR LINE 1-3, 10K FEET**



**FIGURE 30 AIRBORNE CALCULATED SECCHI VISIBILITY VALUES VS SEA TRUTH SECCHI VISIBILITY VALUES
FOR LINE 4, 10K FEET**

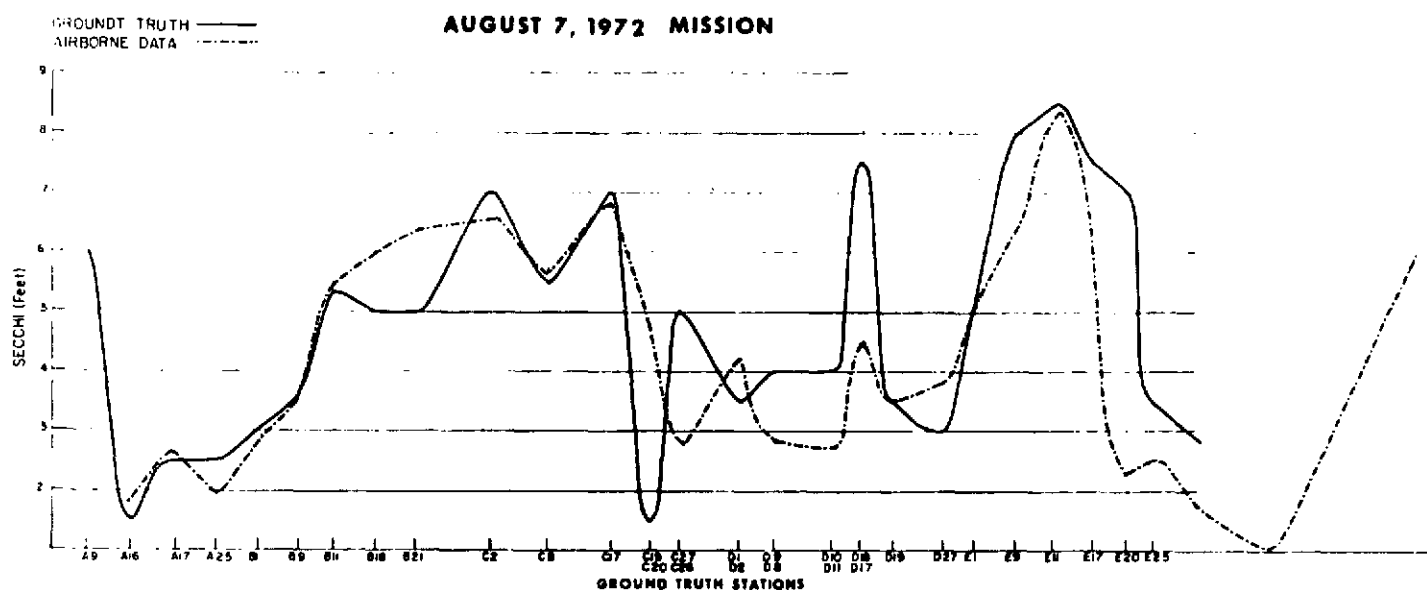


FIGURE 31 AIRBORNE CALCULATED SECCHI VISIBILITY VALUES VS SEA TRUTH SECCHI VISIBILITY VALUES FOR LINE 5, 10K FEET,

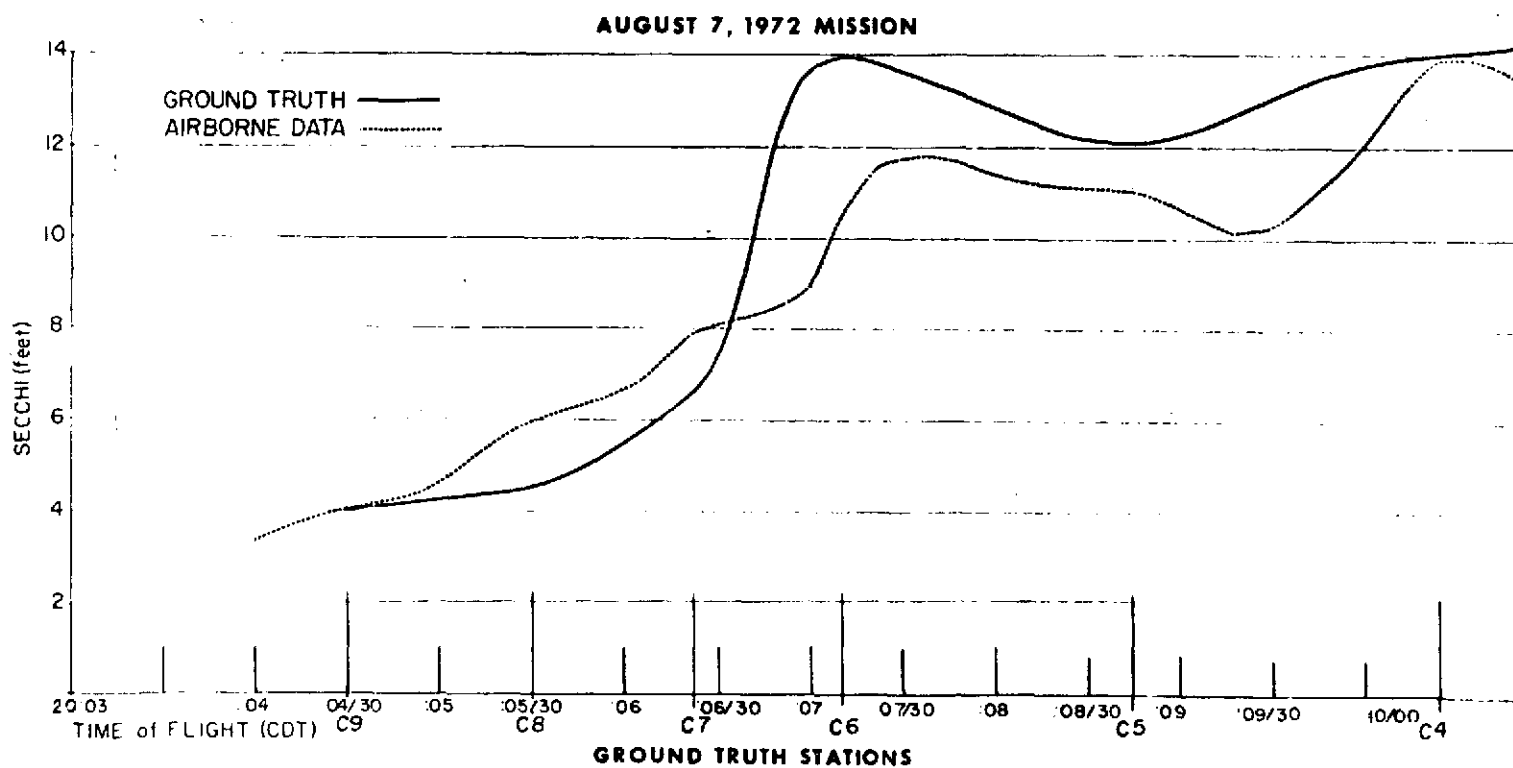


FIGURE 32 AIRBORNE CALCULATED SECCHI VISIBILITY VALUES VS SEA TRUTH SECCHI VISIBILITY VALUES FOR LINE C2, 10K FEET

SUMMARY AND CONCLUSIONS

The primary objective of this phase of the water color investigation was to determine if chlorophyll and secchi visibility sea truth measurements could be correlated with data collected by a spectral radiometer over coastal waters. The preliminary results of this study have indicated that it is possible to correlate airborne derived values for these parameters with corresponding sea truth for certain ranges of these measurements.

The accuracy of the low altitude (2.5K feet) airborne derived chlorophyll values in the $0-5\text{mg}/\text{m}^3$ range is $\pm 20\%$. The ratio method used in the investigation does not compensate for the non-linearity of the relationship above $5\text{mg}/\text{m}^3$. Therefore, above $5\text{mg}/\text{m}^3$ the chlorophyll correlation becomes progressively worse. The accuracy of the high altitude data (10K feet) on a clear day, with low haze, approaches that obtained at low altitude.

The non-linearity experienced in the chlorophyll relationship is not as pronounced in the secchi visibility measurements obtained during this experiment. This non-linearity may exist for values of secchi over 10 feet. Only a few secchi readings above ten feet were obtained during this investigation and the behavior of the algorithm for greater secchi visibility depths was not evaluated.

The secchi correlation on most of the flight lines is within the error that is expected by the inaccuracies in reading the secchi disk and the changes in water conditions that could be experienced by aircraft and boat location error. The main exception to this is the discrepancy between the sea truth and the airborne data in the last half of the August 4, 10K feet mission (Figure 29). The reason for this difference is not known.

A large part of the deviation between the airborne and sea truth chlorophyll and secchi visibility measurements can probably be attributed to the

sea truth values with which the airborne data was compared. In a number of cases the sea truth was collected three to four hours before or after the flight of the aircraft. Also, the aircraft, in only a few cases, flew over the exact area in which the sea truth was obtained. In a dynamic body of water like the Mississippi Sound this could have a marked effect on the accuracy of comparing the airborne data with the sea truth.

The study also indicated that the accuracy of the airborne data can also be improved by adding corrections to the chlorophyll and secchi visibility algorithm for changes in sun angle, altitude and the non-linearity of the relationships.

REFERENCES

1. Clark, G.L., G. Ewing and C. Lorenzen. 1970. Spectra of backscattered light from the sea obtained from aircraft as a measure of chlorophyll concentration. *Science*, 167, 3921.
2. Hanson, Kirby J. 1972. Remote sensing of the ocean. Remote Sensing of the Troposphere. U.S. Department of Commerce.
3. Lockheed Electronics Company, Inc. 1973. User documentation Phase II, IR Spectral Radiometer Program. 22-1-22-38.
4. Arvesen, John C., E.C. Weaver and I.P. Millard. Rapid assessment of water pollution by airborne measurement of chlorophyll.
5. Boudreau, R.D. Personal communication. NASA, Earth Resources Laboratory.
6. Atwell, B.H. Personal communication. NASA, Earth Resources Laboratory.
7. Atwell, B.H. Mississippi Sound Remote Sensing Study, ERL Report No. 048, Earth Resources Laboratory, Johnson Space Center, Bay St. Louis, MS, April, 1973.
8. Yentsch, C.S. The influence of phytoplankton pigments on the color of sea water. *Deep-Sea Research*, Vol. 7, 1960.

APPENDIX

SEA TRUTH

Flight lines from four missions were selected for the first evaluation of spectral radiometer data. A summary of the sea truth data and collection procedures are included in this report for reference purposes. The detail collection, and laboratory procedures and additional measurement data is contained in the sea truth report on each mission. The four missions are as follows:

I. Mission - Water measurement for Goddard Space Flight Center Spectrometer

Water Color Study, Mississippi Sound area, July 24, 1972. Earth Resources Laboratory, Report No. 19.

Mission Area - Middle of Mississippi Sound from Bay St. Louis to west tip of Dauphin Island.

Sea Truths - 24 sample stations along flight lines. Four sea truth boats utilized. Two measurements obtained at each station except only one measurement from stations A6, B6, C6 and D6.

Meteorological Data - Sky clear; however, considerable haze and smoke.

Measurement Summary Chart - (Table 1)

II. Mission - Multispectral Line Scanner (M²S) Evaluation, Mississippi Sound area surface measurements, August 4, 1972, Earth Resources Laboratory Report No. 028.

Mission Area - Middle of Mississippi Sound from Bay St. Louis to west tip of Dauphin Island.

Sea Truth - 24 sample stations along flight line. One sea truth boat utilized. One measurement obtained at each station.

Meteorological Data - Sky clear of clouds and visibility was seven miles.

Measurement Chart - (Table 2)

III. Mission - Biloxi Bay Study, October 18, 1972.

Mission Area - Middle of Back Bay of Biloxi, Biloxi Bay and between Deer Island and Biloxi Beach.

Sea Truth - Fourteen sample stations were located along the three flight lines.

Meteorological Data - 20% cloud cover below flight line, heavy haze.

IV. Mission - Mississippi Sound Remote Sensing Study, August 7, 1972, ERL report No. 025.

Mission Area - Mississippi Sound from east of Bay St. Louis to the middle of Dauphin Island and extending south ten miles outside of the Mississippi Sound Barrier Islands.

Sea Truth - Sampling stations were based on a 3-mile grid system throughout the test area.

Meteorological Data - Sky clear of clouds.

Measurement Summary Chart - (Table 3)

Table 1
MEASUREMENT SUMMARY CHART
July 24, 1972 Mission

Station	Secchi Visibility Ft.				Chlorophyll mg/m ³				Water Depth Ft.			
	A	B	C	D	A	B	C	D	A	B	C	D
1	5.5	5.5	4.5	5.5	1.999	2.552	2.504	7.880	12	18	18	12
2	6.0	5.5	4.0	3.5	2.955	2.002	4.034	16.978	10	16	16	13
3	5.0	8.0	7.0	4.0	3.339	1.271	2.857	4.932	15	16	16	16
4	5.0	8.0	5.5	5.5	3.218	1.247	2.793	1.510	14	14	15	10
5	5.0	8.5	5.5	8.5	3.930	1.810	2.737	1.160	14	16	11	12
6	5.5	10.0	6.0	8.0	3.009	1.563	3.388	1.197	16	14	16	15

Table 2

MEASUREMENT SUMMARY CHART
August 4, 1972 Mission

Station	Secchi Visibility Ft.				Chlorophyll mg/m ³				Water Depth Ft.			
	A	B	C	D	A	B	C	D	A	B	C	D
1	3.5	4.0	10.0	4.0	2.9	3.0	1.0	3.9	6	16	15	14
1	4.0	6.0	8.0	6.5	1.5	2.1	2.9	3.2	7	16	15	12
2	4.5	6.0	8.0	6.0	2.5	-	1.6	1.7	7	16	13	15
2	4.0	6.5	8.0	6.0	0.2	0.8	1.1	3.6	7	16	18	16
3	4.0	6.0	8.5	6.0	2.5	2.1	1.7	3.9	13	16	12	16
3	4.5	8.0	6.0	6.0	2.0	1.6	1.3	2.3	13	16	15	15
4	4.5	6.5	8.0	8.0	1.8	1.2	2.1	4.4	13	14	15	10
4	4.0	10.0	6.5	6.5	1.5	1.1	1.6	4.3	13	18	15	14
5	4.5	9.0	8.0	10.0	2.5	1.0	1.2	2.2	14	17	20	15
5	4.0	10.0	5.5	6.0	2.2	1.3	1.9	8.7	14	19	12	16
6	4.0	11.0	6.5	12.0	2.6	1.3	1.7	1.0	15	20	10	18

Table 3
MEASUREMENT SUMMARY CHART
August 7, 1972 Mx

Sta.	Secchi Visib. ft.	Chloro. mg/m ³	Water Depth ft.	Sta.	Secchi Visib.	Chloro. mg/m ³	Water Depth
A8*	5/1.5	2.4/3.7	12/6*	C26	5	3	12
A9	6	6.1	8	C27	1.5	8.8	6.5
A10	6	2.6	8	D1	3	10	8
A15	1.5	3.9	25	D2	3.5	5.3	14
A16	1.5	3.5	10	D3	7	1.9	17
A17	2.5	2.4	11	D7*	5/7	2.1/2.4	14/13
A23	2.5	2.2	14	D8*	2.5/4	4.5/2.4	12/11
A25	2.5	2.6	.2	D9*	2.5/2	4.7/7.2	7/6
B1	3	3.6	8.5	D10	2	2.9	6
B7*	3.5/4	4.4/4.1	9/9	D11	4	2.2	8
B9*	4.5/5.6	3.4/2.5	9/9	D17	7.5	2.0	15
B11	5.3	1.4	25	D18	3.5	6.9	7
B17	6	2.5	12	D19*	4/3.5	6.8/11.4	11/11
B21	5	2.5	13	D20*	8/5	3.1/5.1	20/16
B22	4.5	1.7	16	D26	7	1.3	16
C2	7	1.9	13	D27	3	11.1	5
C3	8.5	2	17	E1*	6/5	-/3.7	12/12
C4	14	1.1	43	E2*	6/6	-/.2	12/18
C5	12	2.2	35	E9*	8/-	-/-	14/16
C6	14	1.4	30	E10*	1/1.5	5.1/3.1	11/11
C7*	8.5/-	1.4/6.5	13/18	E11*	8/8.5	2.5/1.4	17/17
C8*	5.5/-	2.2/4.5	13/16	E12*	10/10	1/5.2	18/18
C9*	5/-	3.2/4	11/12	E16*	4/-	5.2/-	16/16
C16	10.5	1.4	24	E17*	.7/7.5	2.3/1.9	15/15
C17	7	1.4	12	E20*	5.5/6	10.7/3.8	12/12
C21*	10/8.5	1/1.9	10.5/11	E21*	6/5.5	3.7/2.4	11/11
				E25	3.5	8.4	6

NOTE: * indicates two sea truth measurements at the same station but a different times.